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Enhancing crop production using hoophouses

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Abstract

An increase in demand for locally grown produce has led to a need for additional knowledge on how hoophouses in the high desert can be utilized to potentially increase quality, yield, and growing season of warm and cool season crops. With as few as 90 frost free days in northern Nevada, these potential benefits of hoophouses are important for local growers. Plant physiological knowledge was applied in two different studies: (1) application of wind to lettuce grown at the production scale using high and low density plantings in hoophouse and greenhouse environments; and (2) potential of hoophouses to enhance yield and extend the growing season of warm and cool season crops. Hoophouses provide a protected environment for growing vegetable crops by reducing wind, but at the cost of natural benefits provided by some level of mechanical stimulation. If wind can be manipulated to generate a higher quality baby salad mix at production scale planting densities, then applying wind has the potential to benefit producers and consumers. Major questions include: (a) how will wind alter leaf characteristics associated with high quality lettuce; (b) can wind generate a leaf response at production scale densities; and (c) what quantity of wind is required. To address these questions, lettuce was grown in hoophouse and greenhouse environments using high and low density plantings under different wind treatments. Wind treatments did not produce desirable leaf characteristics in any of the different set of experiments and thus is not a practical cultivation technique in northern Nevada. Three additional sets of studies determined if hoophouses in northern Nevada provide environmental conditions sufficient to increase yield and extend the growing season of warm and cool season crops. Hoophouses outperformed field plots in terms of yield, regulating environmental plant stressors, and managing rodent problems. Winter crops planted in early October generated harvestable produce throughout the winter months with the added protection of hoophouses and a headstart on spring harvest. In addition, early season extension was successfully applied to hoophouse grown tomatoes.

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Chapter 1: Introduction

Hoophouse use in the high desert is increasingly important because of its potentially beneficial effects on plant growth, regulating plant microclimate, and generating higher quality produce. Plant physiological knowledge is an important tool to understand how hoophouses achieve these potential benefits. Greater understanding in turn benefits local producers and consumers. Thus, a major focus of this thesis was to investigate if plant physiological knowledge enhances hoophouse production of seasonal crops.

Mechanical stimulation refers to any process that causes plant movement and subsequently modifies plant growth and development. Wind is one of the most common mechanical stimuli and, when applied during plant growth, is an important factor in plant developmental strategies. Studies of mechanical stimulation have mostly focused on brushing leaves, which generates the 'touch' response through physical contact, and its effect on plant morphology (Jaffe, 1973). However, brushing has potential disadvantages. One drawback is potential damage to plant tissue (Mitchell, 1994; Garner and Bjorkman, 1996). Another drawback is the practicality of applying the brushing technique to plants grown at the production scale. Other forms of mechanical stimulation have been studied along with numerous plant species, but differing plant response prompts a need for additional research in this area.

Hoophouses are becoming an increasingly important structure for cultivating vegetable crops, especially in climates where extreme weather events are common. Hoophouses protect plants from high winds and can reduce wind speeds by approximately 35% inside the hoophouse compared to outside (Zhao and Carey, 2009). Wind reduction within a hoophouse has advantages in extreme situations, but may be a disadvantage by reducing mild mechanical stimulation and subsequently the natural benefits received by plants. Additionally, some level of flexing in response to wind can generate stronger plants, which in turn are more resistant to future stressors and damage during harvest (Whitehead, 1961; Clarkson, 2003).

Growers in northern Nevada can successfully grow baby salad mix ten months out of the year, from fall through spring, using hoophouses for seasonal protection. Hoophouse lettuce is grown at high plant densities, which can increase elongation and decrease leaf thickness (Garner and Bjorkman, 1996). These leaf characteristics can decrease lettuce quality and postharvest processability, which can reduce shelf life of lettuce (Clarkson, 2003). One approach to optimize lettuce quality is to apply plant physiological knowledge about mechanical stimulation to hoophouse grown produce. Thus, intensively cultivated crops such as baby salad mix may benefit from mechanical stimulation if wind is able to generate the level of stimulation required to produce a more desirable crop. In order to produce a consistently high quality lettuce from mechanical stimulation, it is important to understand the interactions among hoophouse microclimate, wind speed, wind duration, and a plant's response. Thus, the overall objective of the first study was to determine the quantity of mechanical stimulation necessary to penetrate densely planted lettuce at the production scale to generate a uniform increase in desirable morphological leaf characteristics.

In addition, extreme diurnal temperature fluctuations greatly limit the growing season in the high desert. The number of frost free days can be as few as 90 days in northern Nevada (Kratsch et al., 2010). However, hoophouses can be used to optimize growth during early spring, late autumn, and through winter in sunny locations because temperatures inside the hoophouse can be 10 °C warmer than in the field (Zhao and Carey, 2009; Wien, 2009). Therefore, hoophouses can be utilized for a wide range of potentially successful crops and meet the increased demand for locally grown fruit and vegetables all year. Hoophouses also provide added benefit of increased plant water use efficiency through a reduction in evaporative demand between 30-40% in hoophouses compared to outdoors (Zhao and Carey, 2009; Orgaz et al., 2005). Disease and pest problems can be reduced to a greater extent in hoophouses than field grown crops when proper cultural practices are initiated (Lamont, 2005; Rogers and Wszelaki,

2012). However, hoophouses reduce photosynthetically active radiation by approximately 15% (Reiss et al., 2004), dependent on cover type. Hoophouses are also susceptible to high day time temperatures during summer months and considerable cooling at night, which may result in plant heat stress and reduced yield (Rogers and Wszelaki, 2012; Ward and Bomford, 2013).

Regardless of the potential benefits and disadvantages, hoophouses have proven effective at increasing both the quality and quantity of fruit and vegetables compared to field grown crops (Lamont et al., 2005; Wittwer and Castilla, 1995; Krizek et al., 2006). However, knowledge on benefits of hoophouses in the high desert is limited. Optimizing crop quality and quantity by applying plant physiological knowledge to hoophouse grown produce may generate knowledge on how hoophouses are a viable way to increase yield and extend the growing season in areas where extreme weather events are common. Thus, the overall objective of the second set of studies was to determine whether hoophouses can increase the yield of heirloom warm and cool season crops compared to field grown crops. In addition, planting date treatments were applied to determine whether season extension is a viable option for growers in northern Nevada to provide quality produce earlier when market prices are higher. The potential benefits provided by hoophouses would allow growers to generate year round produce for local markets and restaurants.

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Chapter 2: The effect of mechanical stimulation on lettuce grown at the production scale: wind applied in hoophouse and greenhouse environments

ABSTRACT

Hoophouses provide a protected environment for growing vegetable crops by reducing wind, which subsequently can reduce mechanical stimulation to plants. Mechanical stimulation is any process that induces plant movement and alters plant growth and development to potentially produce stronger and stockier leaves. If wind can be manipulated to generate a higher quality baby salad mix, then application of mechanical stimulation has the potential to benefit producers and consumers. High quality lettuce also is better able to withstand harvest and processing as well as an increased shelf life. The practicality of applying mechanical stimulation through wind at production scale densities in variable growing environments is a major question for hoophouse production. To address this question, lettuce was grown in hoophouse and greenhouse environments using high and low density plantings under different wind treatments. Applying wind treatments of 30 minutes of daily wind duration and 6 m s^{-1} wind speed to lettuce grown in hoophouses at high density plantings resulted in a whole leaf fresh market mass decrease, but specific leaf area (SLA), which is an indicator of leaf quality, was not significantly affected by wind treatments. No significant plant response to wind treatments was measured in the high density greenhouse plants. In contrast, SLA and whole leaf fresh market area increased in plants grown in the low density greenhouse experiments at 6 m s^{-1} wind speed under differing wind durations. Although these characteristics are considered important for lettuce processing and marketability, the increased SLA in response to wind in the low density greenhouse experiments generated the opposite of what is deemed high quality lettuce. Because the effect of wind on leaf characteristics was not consistent across the different sets of experiments and did not produce desirable characteristics, application of wind to improve quality of hoophouse-grown lettuce does not appear to be a practical cultivation technique.

INTRODUCTION

Mechanical forces as natural plant disturbance have been studied in the environment for over a century (Darwin, 1881). In the natural environment, exposure to various forms of mechanical stimulation produce stronger, stockier plants more resistant to future stressors (Coutand, 2010). The term "mechanical stimulation" refers to different processes that induce plant movement and subsequently alter plant growth and development. Wind is one of the most common stimuli found in nature and, when applied during growth, is an important factor in plant developmental strategies.

Studies of mechanical stimulation have mostly focused on brushing leaves, which generates the 'touch' response in plants and its concomitant effect on plant morphology (Jaffe, 1973). Brushing generates a considerable plant response at low application rates, whereas wind exposed plants require a longer duration of exposure to gain similar results (Mitchell et al., 1977; Latimer, 1990; Beyl and Mitchell 1983). One potential disadvantage of using the contact method of mechanical stimulation is damage to plant tissue (Mitchell, 1994; Garner and Bjorkman, 1996). Another drawback to brushing is the level of practicality when plants are grown at the production scale. Commercial application of the brushing technique is difficult and generally applied on grow benches to condition seedlings for transplant (Bjorkman, 1998). Other methods to stimulate movement include overhead water sprinkling, wind, vibration, or shaking (Mitchell, 1994). Different forms of mechanical stimulation generate variable responses in leaf morphology, which also vary among plant species. Differing plant response prompts a need for additional research in this area.

Hoophouse use for vegetable production has recently increased, especially in areas where variable climate and short growing seasons are common. Growers in northern Nevada have successfully grown profitable baby salad mix from late-August through mid-June when using hoophouses for seasonal protection (Kratsch et al., 2010). Hoophouses provide protection from

frost, extreme winds, and generate a more stable microclimate, but at the cost of natural benefits provided by some level of mechanical stimulation. Physical characteristics perceived through organoleptic perception, such as color, texture, and firmness, are important factors when consumers purchase fresh produce. Chefs prefer the third harvest from lettuce plants because leaves are tougher, thicker, and lay on the plate better. When mechanical stimulation is applied early in growth, plants often show a greater degree of greenness than control plants due to an increase in chlorophyll content per unit dry weight (Biddington and Dearman, 1984; Biddington and Dearman 1985a; Latimer, 1991; Mitchell et al., 1975). Brushing baby leaf lettuce plants also increased cell wall strength that produced a thicker and stronger leaf for harvest and handling (Clarkson et al., 2003). Third, a positive correlation was found between leaf dry matter content and shelf life of lettuce after industrial processing (Clarkson et al., 2003). Furthermore, plants that develop while exposed to high wind speeds during early stages of plant development produce leaves with modified morphology capable of withstanding future stressors (Whitehead, 1961). Thus, mild mechanical stimulation applied to lettuce via wind during winter when environmental conditions promote thinner and elongated leaves may benefit producers on a production scale if wind can be manipulated to generate leaf characteristics desirable to local consumer and to optimize lettuce quality.

Certain morphological leaf characteristics are correlated with lettuce quality and are altered by mechanical stimulation. The ‘touch’ response results in a reduction of leaf elongation and specific leaf area (SLA), but an increase in leaf thickness (LT), fresh specific leaf mass (SLM_f) and leaf dry matter content (LDMC; a measure of density) (Clarkson et al., 2003; Biddington and Dearman, 1985a). Increased dry weight correlates to an increase in leaf firmness (Clarkson et al., 2003). Mechanical stimulation applied during early stages of leaf development may cause SLA to decrease to a greater extent than if applied as a leaf reaches maturity (Latimer, 1991). SLA is a measure of leaf thickness (LT) because LT is directly proportional to SLA

(Latimer and Severson, 1997; Clarkson et al., 2003; Vile et al., 2005; Anten et al., 2010). SLA fluctuates due to environmental temporal and spatial variation (Wilson et al., 1999), and shading due to high plant densities may also alter SLA. Effects of mechanical stimulation on leaf characteristics are both directly and indirectly linked to lettuce quality.

Seasonal climatic differences have an effect on the degree of leaf response to mechanical stimulation. The effect of mechanical stimulation is more prominent during environmental conditions conducive to elongation (Heuchert and Mitchell, 1983), and low light levels intrinsically increase elongation (Latimer, 1991). Leaf dry mass decreased when broccoli was treated with wind at speeds of 7 m s^{-1} for 5 minutes in the morning and again in the evening during the summer. However, during fall treatments, plant response to mechanical stimulation was amplified, and stem length, leaf area, leaf dry mass, and shoot dry mass all decreased (Latimer and Severson, 1997). The microclimate of hoophouses during lettuce production corresponds with conditions that typically generate the greatest potential for leaf response from mechanical stimulation.

Leaf response to mechanical stimulation is also affected by space among plants. Increased space among plants reduces dependability on neighbors for support, reduces competition for light, and increases wind load experienced by plants, which in turn reduce leaf elongation (Harris et al., 1973). Space allows for greater plant wind sway and therefore morphological response (Mitchell et al., 1975). At the production scale, seed sowing densities are high, and lettuce plant stems are often 0.5 cm or less apart at soil level to increase economic benefit per area available (Fig. A.1; personal communications from local farmers and at the Desert Farming Initiative (DFI), University of Nevada, Reno). Therefore, plants are intrinsically faced with competition for light, nutrients, and water. Due to high plant densities, elongation tends to occur due to a shade avoidance response. Shade avoidance is characterized by morphological changes such as increased petiole elongation as well as a reduction in leaf area and

lamina thickness (Garner and Bjorkman, 1996). However, during early developmental stages of growth when mechanical stimulation is applied, plants are not overly crowded and experience greater wind sway than later in growth. Thus, intensively cultivated crops such as baby salad mix may benefit from mechanical stimulation if wind is able to generate the appropriate leaf bend and level of stimulation required to produce a more desirable crop.

An important hurdle to produce a consistently high quality lettuce from mechanical stimulation is to understand interactions and interdependencies among wind speed, wind duration, total wind dosage, numerous environmental variables, and a plant's response. It is difficult to deduce the source of morphological leaf change, whether from leaf temperature change, plant water relations, or actual physical movement of leaves (Biddington, 1986). However, physical movement is an underlying cause of change to leaf morphology (Smith and Ennos, 2003; Jaffe, 1973), and the total daily dosage of mechanical stimulation applied to plants is more important than the frequency of application (Beyl and Mitchell, 1977). In addition, plants grown outdoors have a greater threshold for mechanical stimulation, and therefore a longer duration of treatment will be required to obtain similar results as greenhouse grown plants (Mitchell, 1996). Lettuce grown at the production scale is subject to variable microclimate, and differences in soil structure and water application. It is unknown how lettuce will respond to wind under production scale conditions, and whether wind speed, wind duration, or wind run (i.e. wind speed multiplied by wind duration) is the contributing factor. Thus, the overall objective of our study is to determine the feasibility and quantity of mechanical stimulation required at a production scale that will not only penetrate densely planted salad mix, but also generate a uniform increase in desirable morphological leaf characteristics.

Major unanswered questions that the current research will investigate are: (a) whether wind will generate substantial mechanical stimulation to alter leaf characteristics associated with high quality lettuce; (b) whether wind speed, wind duration, or an additive effect of both cause

change in leaf morphology; and (c) the feasibility of generating leaf response with applied wind at a high density production scale. Answering these questions involves two sets of studies to determine the level of plant response and feasibility of implementing mechanical stimulation: (i) controlled-environment greenhouse experiments that investigate wind speed, wind duration, daily wind run, and associated morphological changes; and (ii) hoophouse experiments that determine whether applying wind at the production scale generates replicable results in a more variable growing environment and high planting densities.

Greenhouses generate a more controlled environment to better isolate wind as the primary factor that potentially affects leaf characteristics. Greenhouse studies were used to determine the relationship among leaf characteristics, wind speed, wind duration, and wind run. Quantifiable leaf characteristics were measured that are beneficial to producers and associated with favorable organoleptic perception. Measurements of specific leaf area, leaf dry matter content, fresh market mass, and number of days of leaf exposure to wind were the main focus, although measurement of air temperature and wind speed helped discern environmental gradients. An initial hoophouse experiment was designed to determine whether a small scale, in situ manipulative experiment could modify the growing environment enough to induce morphological leaf change. Subsequent greenhouse studies were conducted to control hoophouse variability using production scale planting density in addition to individual container plants. Supplemental hoophouse studies were used to determine whether the greenhouse response could be generated and maintained at the production scale despite greater variation in growing conditions. Hoophouse studies also examined whether mechanical stimulation applied via fans, compared to natural hoophouse conditions, generates a large enough response to warrant the use of fans throughout the growth cycle.

MATERIALS AND METHODS

Hoophouse Experiments

A salad mix of three *Lactuca sativa* varieties ‘Green Saladbowl’, ‘Prize’, and ‘Red Saladbowl’ was grown under the Desert Farming Initiative (DFI) hoophouses at the Valley Road Field Laboratory, Nevada Agricultural Experiment Station, University of Nevada, Reno (Fig. A.2). Studies were conducted in three hoophouses. Two hoophouses were 100 x 20 feet; one oriented north-south (hoophouse (HH) 3), the other east-west (HH2). The final hoophouse was 120 x 20 feet and oriented east-west (HH6). Many growers alternate lettuce varieties within a single raised bed to increase efficiency during harvest and subsequent cleaning and packaging. Because plant species respond differently to mechanical stimulation, all three lettuce varieties grown at DFI were included in this study to investigate potential varietal differences.

During the spring 2016 experiment, three hoophouses each contained three treatment-control pairs for a total of nine pairs of study areas (Fig A.3). Spring 2017 experiments were set up in one hoophouse with two replicates. Both hoophouse experiments were laid out in a stratified random block design. Steel structures welded at 5’ W x 4’ L x 2’ H were placed around each treatment area to confine wind flow generated from a fan to that treatment plot. The three sides oriented opposite the fan were wrapped in clear Mylar, with the top and fan side open. Control areas were not given barriers during the 2016 experiment in order to represent natural hoophouse conditions. Spring 2017 included two control areas, one with a Mylar barrier to eliminate natural leaf movement and the other without. Fans were placed approximately four inches from the start of the first row of lettuce and on the north or east sides of the raised bed to avoid shading plants. Four two-dimensional sonic anemometers (Model DS-2, Decagon Devices, Inc., Pullman, WA), calibrated August 2015, were used to determine wind speeds within the treatment area. The DS-2 anemometers were connected to an EM50 datalogger that collected data every 5 seconds and recorded the average every minute.

During the spring 2016 hoophouse experiment, mechanical stimulation was applied to lettuce for 10 minutes in the morning and again for 10 minutes in the evening using unidirectional 20-inch box fans with 2,500 CFM at the highest setting. Wind speed within the treatment area was quite variable ranging from 1.0 m s^{-1} to 4.0 m s^{-1}. However, wind speed was consistent at specific locations within the treatment area, between houses, and over time. Five plants of *Lactuca* 'Green Saladbowl' and five of *Lactuca* 'Prize' were randomly selected within the treatment area at both 1.0 m s^{-1} and 4.0 m s^{-1}. The control area was similarly spatially sampled for ten plants of each variety of lettuce.

For the spring 2017 experiment, high-velocity 20-inch fans (Utilitech Inc.; Pennsylvania, USA), with a maximum CFM of 6800, were used to generate higher wind speeds across the treatment area. Mechanical stimulation was applied to two of the treatment areas for 5 minutes in the morning and another 5 minutes in the evening, while the remaining two treatment areas received 15 minutes in the morning and again in the evening. Each treatment area contained two wind speeds, 2.2 and 6.6 m-s^{-1} (in the remainder of the text, these speeds are referred to as 2 and 6 m s^{-1}, respectively). Each treatment was paired with the two different control areas. All treatment and control sites had a sample size of ten plants. Only *Lactuca* 'Red Saladbowl' was used.

Microclimate

Three anemometers were placed at predetermined locations within the treatment area and one in the control area. After placement, each sensor was leveled and oriented north. The anemometer sensor platform was placed just above leaf canopy to measure wind at the boundary layer of plant foliage. Sensors were raised twice a week to ensure a measure of wind at the boundary layer. To reduce stress to plants, mechanical stimulation was applied when temperatures were above 10 °C, which occurred at 0930 and 1700 local time.

Air temperature was measured using a CR10T datalogger, which records data over time, and two 107-L temperature probes (Campbell Scientific, Inc., Logan, UT, USA). Aluminum foil

cones were placed over the probe to reduce direct heating from the sun. Temperature was also collected to determine whether air temperature differed within the Mylar enclosed treatment area versus the open control area. Results showed no difference. Measurements were made every 5 seconds and averaged over and recorded every minute. Equipment was rotated to a new treatment-control location every Monday and Thursday for inter-house comparison.

Greenhouse Experiments

Greenhouse studies were conducted at the Nevada Agricultural Experiment Station Valley Road Greenhouse Complex. Temperatures were maintained between 18 – 22 °C and no supplemental shade was used over the greenhouse. Two types of greenhouse experiments were conducted: one that used large planting trays to mimic high density production crop management, and the other used isolated containers of plants to more accurately apply wind treatments. For the tray experiment, each treatment and control area was 32” x 32” using four 16” x 16” x 6” trays (Stuewe and Sons., Inc., Tangent, OR, USA). This design best mimics the hoophouse production scale three foot wide raised beds planted at high density. Soil was composed of one part triple mix of topsoil, humus, and compost to one part organic compost (Oxborrow Trucking & Landscape Materials; Reno, NV) and sterilized prior to use by heating the soil to 95 °C for 30 minutes. The high density experiment was harvested early October 2016.

The container experiment used 3” diameter cone-tainers (Stuewe &Sons, Inc.) to isolate plants and generate low plant density. A general purpose organic soil mix was used (Berger OM6, Berger Company, Inc.). The first low density experiment began late October 2016 and the fifth commenced in August 2017. The final two low density experiments are referred to as subset greenhouse experiments because additional leaf measurements were taken. Each plant received the same soil medium, fertilization and irrigation regardless of the experimental design. Peters Professional 15N-16P-17K (Peat-Lite Special; Everris NA, Inc.) was added at 296 ppm N starting when plants germinated, and continued weekly throughout the growing cycle. Fertilizer was

applied consistently across all plants. Irrigation was installed at soil level to avoid any additional mechanical stimulation to plants.

Two lettuce varieties were studied in the greenhouse experiments. *Lactuca sativa* variety 'Red Saladbowl' is grown locally and preferred by chefs and consumers alike whereas a 'Lollo Rossa' type leaf was used in both Clarkson et al. (2003; 2005) studies and exhibited significant morphological changes as a result of mechanical stimulation. During the tray experiment, 'Red Saladbowl' and 'Lollo Rossa' varieties were sown in alternate rows with 2 inches between rows and 60 seeds/foot (Fig. A.4.A). The high density chosen correlates to commercial seeders available on the market and densities preferred by local growers in hoophouses. Container experiments had five plants per container, in which adjacent plants did not hinder growth and wind speed (Fig. A.4.B).

As plant density increases, leaf movement may generate turbulence and alter wind speeds within a treatment area. To account for this, wind speeds were measured when leaves were 1 cm in length as the treatments began, again when leaves reached 5 cm, and at final harvest when leaves were approximately 9 cm. Wind was measured every 5 seconds and averaged over a minute for 10 minutes using sonic anemometers. Continuous measurement of wind would cause uneven treatment because the anemometers block wind flow and shade neighboring plants.

The greenhouse experiments were set up as an incomplete split-split-split plot design with four levels of wind duration as the whole plot, including the control, three levels of wind speed as the split plot within duration, and three true leaves per plant were used for response measurements. Each wind duration treatment had triple replicates totaling nine treatment areas and three controls (Fig. A.5). One tray experiment and five container experiments were run over the course of a year. The three treatment areas received mechanical stimulation in the morning and evening beginning at 8:00 am and again at 5:00 pm for 5, 10, and 15 minutes resulting in a daily total of 10, 20, and 30 minutes, respectively. Five minutes was chosen due to a previous

experiment conducted by Pontinen and Voipio (1992), where 5-6 m s^{-1} of wind was applied for five minutes in the morning for 10 days and did not show significant difference over control when harvested at 5 cm. Ten minutes in the morning and again in the evening as applied during the spring 2016 hoophouse study was repeated. The remaining duration included 15 minutes in the morning and again in the evening to generate ample leaf bends at lower wind speeds and high density plantings as well as to determine whether an upper limit exists for treatment duration as does with brushing. Within each treatment area, three wind speeds were studied at set locations measured by the anemometer; 2.2, 4.5, and 6.6 m s^{-1} (in the remainder of the text, these speeds are referred to as simply 2, 4, and 6 m s^{-1}, respectively). Each experimental variation generated a sample size of n=10. The subset greenhouse experiments only included the control, 10 and 30 minutes of wind duration, and 2 and 6 m s^{-1} wind speeds. Only one true leaf was harvested during each replicate experiment. To reduce spatial effects, the location of each treatment and control were determined through a randomized block design. The two varieties were also randomly assigned within each replicate.

Wind run (km d^{-1}) is the product of wind speed (m s^{-1}) and wind duration (min d^{-1}) for any given treated sample. Table 2.1 details the specific wind duration and wind speed treatment combinations and their corresponding wind runs that were examined in the low density greenhouse experiments. This design will provide information on whether wind speed, duration or total daily wind exposure causes morphological leaf change.

Plant Measurements

In-situ leaf measurements

The duration of an individual leaf's exposure to wind was determined by time of leaf emergence to date of harvest. Plants reach maturity and typically would be harvested by producers for market at around 21 days. New leaves were not counted until at least 1 cm in length. Stimulation was applied for 21, 17, and 13 days to the third, fourth, and fifth true leaves

respectively. Some variation occurred due to the nature of plant growth. Observations were made on even days. Care was taken to avoid touching the plant during measurement. Leaves were randomly selected to measure leaf movement at each wind speed as well as among varieties. Angle of bending and how many times the plant flexed back and forth were determined with video and photographs that were obtained at different stages of plant development.

Harvest

Because suggested harvest times include either 2-3 hours after sunrise or 3-4 hours before sunset to offset any influence of diurnal variations (Garnier et al., 2001), our harvests occurred during early morning and late afternoon and after watering when leaf cells were most turgid. Care was taken to minimize handling and damage to leaf tissue during harvest. The entire plant was pulled and immediately placed in plastic sealable bags with a breath of air to maintain turgor, and then kept in a cool and dark environment for the remainder of harvest until processing. Hydration via humidification has been deemed sufficient for saturation (McMillen and McClendon, 1983) and removed any dehydrating effects on leaves due to long processing time between the first sample and the last sample. Leaves considered for analysis were of marketable quality only. Non marketable quality leaves included damage from pests, torn leaf, tip burn, and yellowing or senesced leaves. Full senescence was considered when a leaf was yellow and not marketable; partial senescence was slight discoloration but still marketable quality. Note was taken to discern the type of damage to determine whether it was wind related. Additionally, not all measurements were made during each replicate experiment.

Leaf area and weight analysis

Individual leaves with known emergence dates were cut just below the node, weighed, and measured for leaf area. All fresh samples were surface blotted before weighing by gently pressing the sample against Kimwipes (Kimtech Science, Inc.) to remove excess surface water. Whole leaf market area (market area) measurements were made using a LI-COR 3000A leaf area

meter with the LI-COR 3050A belt conveyer (LI-COR Biosciences Inc., Lincoln, Nebraska USA) during the subset greenhouse container experiments only. Due to the curly nature of the lettuce varieties chosen, care was taken to flatten leaves before placing through the leaf area meter to establish uniform measurements among all leaves.

Two to five disc samples were punched from each leaf avoiding veins, edges and injured tissue using a sharpened brass cork borer at the leaf lamina. One disc was taken from the upper leaf tip and the remaining discs were collected from alternate lobes, beginning directly below the leaf tip. The location of the disc samples were replicated among all leaf samples where adequate leaf tissue was available. The cork borer diameter was recorded, which was then used to determine leaf area. All the discs from one leaf were pooled together to generate a single sample. The pooled discs were immediately weighed on a microgram scale for fresh weight and placed in a small plastic bag with a paper towel and de-ionized (DI) water to hydrate at approximately 4°C overnight. Vascular samples were obtained using a utility knife to cut approximately an inch of the main stem from the remaining leaf area during the subset greenhouse container experiments only. Stem area was measured using the LI-COR leaf area meter. After weighing, samples were dried in a forced-air electric oven at 60 °C for at least 48 hours. From these measurements, specific leaf area (SLA), leaf dry matter content (LDMC), and fresh specific leaf mass (SLM_f) were calculated using the following formulas:

SLA = fresh leaf area (mm^2) / oven-dry mass (mg)
LDMC = (oven-dry mass (mg) / fresh-mass (mg)) * 100
SLM_f = fresh leaf mass (mg) / fresh leaf area (mm^2)

Statistics

Analysis of variance (ANOVA) with the linear mixed effects model in R software was used for all comparisons. The wind treatment factor in ANOVAs was structured in two ways. First, because the two factors of wind speed and wind duration created an incomplete block design (i.e. it is impossible to create treatment combinations of zero wind duration and any wind

speed, or of zero wind speed and any wind duration), a composite factor was created that combined each pair of treatments into a single factor. This composite factor, designated as "Duration_Speed" in ANOVAs, allowed us to examine the extent that wind duration or wind speed influenced leaf characteristics. Prior to creating the composite factor, ANOVAs were run with wind speed and wind duration as individual factors in a split-split-split-plot experimental design. Although these ANOVAs generated results that were consistent with those from the composite factor ANOVAs, mean comparison could not be completed from the individual factor ANOVAs because of missing cells in the incomplete block design (results not shown). Second, because previous literature indicated that total daily dosage of mechanical stimulation may be most important for affecting leaf characteristics, wind run (which is the product of wind speed and wind duration measured as meters per day) was used as the wind treatment factor in this second set of ANOVAs, except for the 2016 high density hoophouse experiment that had only one wind duration. ANOVA factors were considered as significant when $P \leq 0.05$. All means were reported from raw data as least square means with standard error. ANOVA assumptions were tested, and data were transformed as necessary. Mean comparisons used general linear hypotheses and the t statistic. Replicate container greenhouse experiments were analyzed together in a single ANOVA to increase statistical power, and each experiment was included as a blocking factor to account for any heterogeneity among experiments due to seasonal changes in growth conditions.

Linear regression was used to test the correlation between SLM and LDMC using Pearson's correlation coefficient to determine whether LDMC could be removed as a measurement from further experiments. These measurements were made during a single hoophouse experiment, the greenhouse tray experiment, and a replicate container experiment using lamina SLM and LDMC. The subset greenhouse container experiments compared whole

leaf market SLM and LDMC. Regression assumptions were tested, and transformations were made as necessary.

RESULTS

Specific Leaf Area

The effect of wind on lamina specific leaf area (SLA_L) varied among the different sets of experiments. Wind treatment did not have a significant effect on SLA_L during both the high density hoophouse experiments (Table 2.2) and the high density tray greenhouse experiment (Table 2.3). The effect of wind also did not significantly interact with true leaf or variety during any of these experiments. However during the 2017 hoophouse experiment, differences occurred among true leaf cohorts (Table 2.2A). The oldest true leaf had a significantly greater SLA_L than both of the two younger true leaves, but the two younger leaf true leaves were not significantly different from one another (results not shown). During the greenhouse tray experiment, significant varietal differences occurred (Table 2.3A). SLA_L of *Latuca sativa* 'Red Saladbowl' was significantly less than variety 'Lollo Rossa' regardless of wind treatment (results not shown).

Low density greenhouse container experiments potentially exposed plant leaves to greater leaf movement. In contrast to high density experiments, SLA_L differed significantly among different wind treatments during low density experiments (Table 2.4). SLA_L of leaves exposed to 6 m s^{-1} wind speed was significantly greater than 2 and 4 m s^{-1} within its respective wind duration (Fig. 2.1A). These results suggest that wind speed rather than wind duration is altering the lamina portion of the leaf. SLA_L for leaves exposed to a wind speed of 6 m s^{-1} were 8%, 12%, and 9% greater than 2 m s^{-1} at 10, 20, and 30 minutes of wind duration, respectively, and similarly greater by approximately 5-10% than the control and 4 m s^{-1} at all wind durations (Fig. 2.1A). The control was not significantly different from either 2 or 4 m s^{-1} in any wind duration treatment. SLA_L of leaves exposed to the lowest wind speed of 2 m s^{-1} at all wind durations was not

significantly different from and only approximately 2% less than SLA_L for leaves of control plants.

During greenhouse container experiments, SLA_L also differed among varieties and true leaves, but again these factors did not significantly interact with wind (Table 2.4). As observed in the greenhouse tray experiment, variety 'Red Saladbowl' had a significantly lower SLA_L than variety 'Lollo Rosa'. Variety interacted with true leaf (Table 2.4). SLA_L of variety 'Red Saladbowl' was greatest in the youngest leaf and decreased as leaf age increased, in which true leaf 5 was significantly less than true leaf 4, which were both significantly less than true leaf 3. Variety 'Lollo Rossa' differed slightly. SLA_L of true leaf 3 was significantly greater than both true leaves 4 and 5, but the two youngest leaves were not significantly different from one another (results not shown).

Wind run also had a significant impact on leaf characteristics during low density container experiments (Table 2.4). However, the wind run factor needs to be interpreted carefully because one wind run often includes different combinations of wind speed and wind duration (Table 2.1), but this design allowed us to look at the total daily dosage of wind compared to either wind speed or wind duration as a cause of leaf change. The SLA_L of leaves treated to 12.0 km d^{-1} wind run were significantly greater than the control by 6% and significantly greater than 1.3, 2.7, and 5.4 km d^{-1} by 9, 8, and 6%, respectively (Fig. 2.1B). Wind run of 130 m d^{-1} was significantly greater than 1.3 km d^{-1} by 6%, whereas SLA_L of the control, 1.3, 2.7, 4.0, and 5.4 km d^{-1} did not significantly differ from one another.

During a subset of container experiments, specific leaf area of lamina (SLA_L), of whole leaf market (SLA_M), and of vascular (SLA_V) parts of the leaf were examined to determine whether the effect of wind on leaf characteristics was more prominent in certain leaf parts. All three measurements of SLA had the same rankings of wind speed and wind duration treatments, which included 2 and 6 m s^{-1} and 10 and 30 minutes. However, some differences in statistical

groupings occurred among the three SLA measurements. For SLA_L, 10 minutes of wind duration and 6 m s^{-1} had a significantly greater SLA_L than 10 minutes and 2 m s^{-1}, but these wind treatments were not significantly different for SLA_M and SLA_V (Fig. 2.2A). All three SLA measurements were greater at 10 minutes wind duration and 6 m s^{-1} wind speed than the control, in addition, 30 minutes and 6 m s^{-1} was greater than the control for SLA_M and SLA_V only. Percent change in SLA_V was greatest compared to the control, whereas SLA_L changed the least.

Market and vascular SLA increased as wind run increased (Table 2.5). Both SLA_M and SLA_V of treated leaves were significantly greater at wind run 4.0 and 12.0 km d^{-1} than the control (Fig. 2.2B). The two varieties were not significantly different in either measurements of market or vascular SLA, but wind run and variety had an interacting effect on SLA_V (Table 2.5). Variety 'Red Saladbowl' had significantly greater SLA_V at wind runs of 4.0 and 12.0 km d^{-1} compared to the control. 'Red Saladbowl' SLA_V was also significantly greater at 12.0 km d^{-1} compared to 1.3 km d^{-1} wind run treatment.

Prior analysis of wind duration and wind speed as separate factors generated results that wind duration was not the significant contributing factor to SLA_L change during the greenhouse container experiments, and the interaction between wind speed and wind duration was not significant (results not shown). Overall, greenhouse wind treatments did not generate significantly thicker leaves compared to the control.

Fresh Specific Leaf Mass

Fresh specific leaf mass (SLM_f, mg mm^{-2}) measured during the spring 2016 hoophouse experiment used saturated leaves via overnight hydration, whereas during the greenhouse experiments, hydration via humidification was used. During spring 2016 hoophouse experiments, lamina SLM_f of control leaves was not significantly different from SLM_f measured at either wind speeds (Table 2.2A). Lamina SLM_f during high density greenhouse experiments (Table 2.3A) as well as whole leaf market SLM_f measured during the subset container experiments were also

unaffected by wind (Table 2.5). Lamina SLM_f of *Latuca sativa* 'Red Saladbowl' was significantly greater than variety 'Lollo Rossa' during high density tray experiments when testing the wind run model, although no wind interaction was present (Table 2.3A). Market SLM_f of 'Lollo Rossa' was significantly greater than 'Red Saladbowl' during the subset container experiments, but there was no wind variety interaction present (Table 2.5).

Leaf Dry Matter Content

Lamina LDMC was not significantly affected by any wind treatment during both high density hoophouse and greenhouse experiments (Tables 2.2-2.3). However, varietal differences were observed in the greenhouse high density experiment. LDMC was greater in variety 'Red Saladbowl' than 'Lollo Rossa' regardless of wind treatment. During the single replicate container experiment, lamina LDMC was greater when treated with 10 minutes and 2 m s^{-1} of wind duration and wind speed compared to leaves treated with 20 minutes and 6 m s^{-1} and the corresponding wind runs of 1.3 and 12.0 km d^{-1} (Fig. 2.3A and B). The effect of wind did not interact significantly with variety, but 'Red Saladbowl' had a higher LDMC than 'Lollo Rossa' (Table 2.4). LDMC of true leaf cohorts also differed and interacted with variety. LDMC of variety 'Red Saladbowl' was greatest in the youngest leaf and decreased as leaf age increased, whereas for variety 'Lollo Rossa', LDMC of true leaf 3 was significantly lower than true leaf 4 and 5, but the two youngest leaves did not differ. During the greenhouse subset experiments, whole leaf LDMC was measured and resulted in more variability than lamina LDMC as a result of wind treatments (Table 2.5). The control and 30 minutes of wind duration at 2 m s^{-1} were significantly different and approximately 10 and 5% greater than both 10 and 30 minutes of wind duration at 6 m s^{-1}. In addition, 30 minutes of wind duration at 2 m s^{-1} was significantly greater than both 10 and 30 minutes at 6 m s^{-1}. All wind speeds, wind durations, and wind runs resulted in whole leaf LDMC being significantly less than the control.

Fresh Market Mass and Area

The effect of wind on fresh whole leaf market mass (mg) varied among the different sets of experiments. During the hoophouse high density experiment, market mass of leaves exposed to a wind speed of 6 m s^{-1} and wind duration of 30 minutes and exposed to a wind run of 12.0 km d^{-1} were significantly less than market mass of leaves in the control wind treatment surrounded by a mylar barrier (Table 2.2; Fig. 2.4). No other treatment combinations were different from either control type. During both greenhouse high density tray experiments and greenhouse low density container experiments, market mass response to wind was not significant (Tables 2.3-2.4, 2.6). The effect of wind duration, wind speed, and wind run on whole leaf market area was significant during the subset greenhouse container experiments (Table 2.5). Market area was greater in leaves treated with 10 minutes of wind duration and 6 m s^{-1} wind speed (Table 2.7).

During the high density hoophouse experiment, market mass of true leaf 3 was significantly less than true leaf 4 and 5, although neither of the younger leaves had a market mass significantly different from the other. During the container experiments, each true leaf cohort was significantly different from each other (Tables 2.4). True leaf 5 had a significantly greater market mass than true leaf 4, which was significantly greater than true leaf 3. Variety and true leaf did interact during the container experiments (Tables 2.4). Market mass of the youngest true leaf was significantly greater than each preceding true leaf as leaf age increased for variety 'Red Saladbowl'. However, variety 'Lollo Rossa' was similar to the true leaf pattern seen during the high density hoophouse experiment. During all container greenhouse experiments, market mass of variety 'Lollo Rossa' was significantly greater than market mass of 'Red Saladbowl' regardless of seasonal differences (Tables 2.4).

Leaf Bend

During the high density experiments, 2 and 4 m s^{-1} generated a leaf bend close to 15 and 40°, respectively. The effect of 6 m s^{-1} on high density lettuce was approximately 60° of bend.

However as new leaves emerged and density increased, leaf movement was generally reduced to a flicker at all speeds. Wind generated a slightly greater leaf bend at each of the wind speeds during the low density container experiments. Leaf bend at 2 m s^{-1} was minimal and approximately 15 – 20° of gentle leaf sway. Leaf movement at 4 m s^{-1} was substantially greater with a 0 - 45° back and forth motion. Leaf bend at 6 m s^{-1} wind speed was maintained between 45 - 80° with substantial leaf flickering.

Leaf Damage

During the 2017 hoophouse experiment, damage from wilt, pest damage or basal rot was approximately 0.4% in the wind treatment area, whereas wilt damage in the control area was slightly more at 0.8%. Sporocarps were equally prevalent on both treated and control plants during high density hoophouse tray experiments at just over 10%. Partial senescence by true leaf 3 was 0.4% more likely in treated plants. During greenhouse container experiments, partial to full senescence of true leaf 3 was still a prevalent occurrence. Compared to control plants, treated plants were 1% more likely to be partially senesced and 2% more likely for full senescence. Leaves began to show signs of senescence not long after 21 days of growth regardless of whether plants received wind treatment or not. Plants from the subset greenhouse experiments were not impacted, and all true leaves were harvested.

SLM and LDMC correlation

Because fresh leaf discs rapidly lost hydration when removed from the bag, measurements of fresh mass for LDMC were very difficult. Correlation between SLM and LDMC was significant (Fig. 2.5). In all cases where comparable measurements were made, SLM was strongly, positively correlated to LDMC, which allowed the removal of LDMC from latter experiments. During a replicate 2016 hoophouse experiment, SLM and LDMC were significantly correlated ($R^2 = 0.86$; $P < 0.001$). SLM and LDMC also were significantly correlated during the high density greenhouse tray experiment ($R^2 = 0.76$; $P < 0.001$). Lamina SLM and LDMC were

significantly correlated during a single replicate container experiment ($R^2 = 0.86$; $P < 0.001$). During the subset container experiments, wind had a lesser effect on whole leaf SLM than whole leaf LDMC (Fig. 2.6A and B). However, SLM and LDMC were still significantly correlated ($R^2 = 0.74$; $P < 0.001$).

DISCUSSION

The effect of wind on lettuce varied among the different planting density and growing environment experiments in our studies. We expected that the greatest benefit of wind treatments would be from the low density greenhouse experiments. Although wind treatments had the greatest effect on leaf characteristics in these experiments, the effect on SLA was the opposite of what was expected. The observed increase in SLA indicates a decreased leaf thickness from wind treatments, i.e. a decrease in lettuce quality. At high planting densities, we expected smaller effects of wind treatments on leaf characteristics. Although wind treatments in the high density experiments did not significantly affect SLA, market mass was decreased at the highest wind speed and wind duration combinations, which would not be beneficial to growers because lettuce is sold on a fresh weight basis. Therefore, wind applied to lettuce production in northern Nevada hoophouses does not appear to be a cultivation method worth implementing, and in fact may be detrimental to lettuce production.

Wind is a complex factor due to the difficulty in partitioning effects on leaf characteristics due to mechanical stimulation, leaf microclimate, and other factors. For example, differences in planting density could change leaf movement because neighboring plants support each other as well as change leaf light microclimate due to self-shading (Mitchell et al., 1975; Anten et al., 2005). Certain leaf measurements, such as SLA and leaf area, are more prone to spatial and temporal influences (Wilson et al., 1999) as well as differing among leaves within a single plant (Witkowski and Lamont, 1991). Leaf damage due to mechanical stimulation has also been of concern (Latimer, 1991; Salisbury, 1963; Whitehead, 1961). During the current

experiments, leaf movement was reduced during high density experiments compared to low density container experiments (personal observation). Additionally, the effects of plant density and leaf movement on leaf morphology were likely confounded by microclimate differences in the hoophouse and greenhouse experiments. Early senescence of the oldest true leaf was more prominent in wind treated plants, but the presence of other damage was more common in control areas. Regardless of spatial and temporal influences on leaf characteristics, LDMC and SLM remained positively correlated when comparable measurements were made.

Wind, physical leaf movements, and effects on leaf characteristics

The effect of mechanical stimulation on morphological leaf characteristics has previously been described as dependent on wind speed and physical leaf movement (Jaffe, 1973; Smith and Ennos, 2003). Although we speculate that leaf response to wind would be reduced due to high plant density, this reduced response was not always the case. During the 2017 high density hoophouse experiment, market mass was reduced by the highest wind speed and longest wind duration treatment, compared to the control surrounded by a barrier. The barrier was implemented to replicate hoophouse plants grown in a closed system. However, the control without a barrier, which was exposed to natural wind movement within the hoophouse, was not significantly different than any wind treatment combination. During winter months, hoophouses remain closed most days, which reduces wind flow and the mechanical stimulation that plants naturally receive. However during the 2017 hoophouse experiment, sides remained open during the entire experiment due to an issue with plant mildew, which likely explains the variability between the two types of control. Therefore, plants within natural hoophouse settings experience some wind through open hoophouse sides during production.

Anten et al. (2005) studied whether high density plantings induce a shade avoidance response that results in plants with increased stem elongation and decreased stem thickness, but no interaction between mechanical stimulation and plant density occurred. At both high and low

plant densities, flexing of plant material reduced elongation and increased thickness (Anten et al., 2005).Plants exposed to mechanical stimulation early in development have shown greater morphological leaf change than when applied as leaves are more mature (Biddington and Dearman, 1985a; Latimer, 1991). During all hoophouse and greenhouse experiments, wind was applied early during leaf growth, i.e. when the first true leaf to be harvested was 1 cm in height. At this stage, plant density was minimal and leaf movement was consistent across wind speeds. However, as more leaves emerged, leaf movement was reduced at all speeds. Structural leaf change occurs under high turbulent wind due to increased leaf movement that in turn generates turbulence from otherwise laminar wind flow (Vogel, 1989). The high density plantings may provide a buffer against wind that reduces the negative response from wind treatments. The reduction in leaf movement and protection provided by adjacent lettuce plants may explain the lack of additional leaf response in the lamina leaf during high density hoophouse and greenhouse experiments.

During low density container experiments, wind increased $SLA_{L,}$ whereas the effect of wind on SLA were not significant during the high density experiments. During container experiments, leaf response to mechanical stimulation occurred with 6 m s^{-1} wind speed compared to the other two wind speeds at its corresponding wind duration. Broccoli and lettuce treated with 7 m s^{-1} resulted in no change in leaf SLM, but a decrease in leaf area and leaf dry mass (Latimer and Severson, 1997; Pontinen and Voipio, 1992) . A wind speed of 2.3 m s^{-1} produced a 75° leaf bend and significantly reduced leaf mass, leaf area and SLM (Anten et al., 2010). In our greenhouse container experiments, 6 m s^{-1} wind speed produced a leaf bend between 45-80° and reduced lettuce quality as measured by SLA and LDMC, although harvested leaves had a larger market leaf area during the subset container experiments compared to the control. Similar to previous literature, wind had a negative effect on lamina and whole leaf characteristics that are associated with a stronger leaf tissue and higher quality lettuce.

The effect of mechanical stimulation generates a very rapid response in plants (Jaffe 1976), which may indicate that the degree of bending from various wind speeds initially has a greater impact on how much a plants growth is altered versus the duration of treatment or wind run. Unlike high density plant experiments, isolated plants experienced consistently greater leaf sway from the time the experiment began to harvest. Leaf bending caused by wind is dependent on species and structure. Therefore, wind speed alone as a comparative measure across species and even varieties has its limitations (Leblanc-Fournier et al., 2014). Wind speed seemed to be the most consistent cause of leaf morphological change, which was most prevalent during the container experiments. On the other hand, the effect of wind duration on leaf characteristics was usually not significant among experiments, and thus the effects of total wind dosage, or wind run, was confounded by wind speed. Various studies have determined the optimal number of back and forth brushing strokes is 40 – 100 and leaf bend range from 40 to 90° (Jaffe, 1976; Clarkson et al., 2003; Anten et al., 2005, 2009, 2010). As reported in previous experiments, longer wind durations were needed to induce a similar plant response to brushing due to less leaf movement from wind (Mitchell et al., 1977; Latimer, 1990; Beyl and Mitchell, 1983). However, it is possible that all three wind durations at 6 m s^{-1} exceeded the optimal amount of mechanical stimulation resulting in a negative leaf response.

Measurements of vascular, lamina, and whole leaf market SLA during subset container experiments did not demonstrate an increase in leaf thickness as a result of any wind treatment combination. The biological response from wind was greatest in the vascular tissue, second was whole leaf market, and least responsive was lamina tissue (Fig. 2.2). Vascular tissue will likely be more impacted by physical movement invoked from wind. A study compared wind exposed plants that were allowed to flex and those that were not, indicating that physical movement was the cause of plant response to wind (Jaffe, 1973). Consistent among studies, physical effects of wind are more prominent than the physiological effects (Smith and Ennos, 2003). Hypocotyl

diameter increased and length decreased in lettuce and tobacco plants due to bending of the stem from brushing treatment (Biddington and Dearman, 1984; Anten et al., 2005). SLA_V increased in plants treated with 6 m s^{-1} compared to the control indicating stem thickness was reduced. Similar to a previous study, weaker more elongated plant stems have been noted as a response to wind in *Helianthus annuus* (Smith and Ennos, 2003). Clearly, wind is a complicated force and has variable effects on plants.

Wind, leaf microclimate, and effects on leaf characteristics

Lettuce is a cold-tolerant green. Ideal growth conditions on sunny summer days are 22 ° day and 15 °C night temperatures. Growth during cooler weather will be halted as daytime temperatures remain below 10 °C (Mefferd, 2017). During the hoophouse experiment, early morning and late evening daytime temperatures did occasionally dip below 10 °C. Lettuce plants grown in hoophouses experienced a greater variation in diurnal temperature range than greenhouse grown plants. Regardless of wind treatment, plants during the greenhouse experiments on average had greater LDMC and lower SLA, therefore higher quality compared to those during the hoophouse experiment (Table 2.2B-2.4B).

Lettuce is adapted to lower light levels and cooler temperatures, so will not naturally etiolate during these conditions. However, high density plants would likely be more prone to etiolation due to intraspecific competition for light, i.e. a shade avoidance response, and therefore increased response to mechanical stimulation (Harris et al., 1973; Garner and Bjorkman, 1996; Anten et al., 2009). In contrast, lateral shade reduced plant response to mechanical stimulation (Henry and Thomas, 2002), and during low light and cooler temperatures, wind had no effect on lettuce (Pontinen and Voipio, 1992). Market mass did not significantly change during either high or low planting densities in the greenhouse experiments. Low density plants did not compete for light compared to high density plants, and all greenhouse experiments were grown in less variable

diurnal temperatures. It is proposed that a shade avoidance response and larger temperature variation during the hoophouse experiment resulted in wind reducing market mass.

Wind alters gas exchange of leaves and can affect leaf physiological functions (Smith and Ennos, 2003) through convection heat exchange as the leaf is exposed to wind. Elevated respiration and increased transpiration rates of plants (Todd et al., 1972) would have a greater impact on plants grown in dry environments such as the high desert in northern Nevada. However, the effect of wind is likely species specific and dependent upon leaf characteristics (Smith and Ennos, 2003). The lamina leaf portion is most directly affected by the microclimate aspect of wind due to physiological functions. This interaction explains the variability in SLA_L that is dependent on light levels, plant density, and temperature during hoophouse and greenhouse experiments. Results were not consistent across experiment types, which could be explained by the temporal and spatial differences among experiments. Hoophouse and greenhouse high density experiments may have provided a buffer against the negative effects of high wind speeds on lamina tissue, whereas the low density greenhouse plants were exposed to more direct wind as indicated by the greater leaf bend and movement. During the low density container experiments, SLA_L demonstrated a similar increase as a result of mechanical stimulation (Anten et al., 2010).

Leaf damage, varietal and true leaf response

Damage to lettuce caused by wind was minimal. As had been suggested, treatment was applied at times when leaf foliage was dry in the hoophouses after morning dew had evaporated (Latimer, 1991). Wet foliage was not a concern during the greenhouse experiments because drip irrigation was applied and humidity was low.

Wind applied early in leaf development conditions leaves to withstand future stressors (Whitehead, 1961). In regards to early senescence, the third true leaf was exposed to the greatest number of treatment days and the only leaf affected. The third true leaf also had the greatest exposure to wind sway. As new leaves emerged, regardless of isolated or high density plants,

leaves created some level of buffer to the other leaves on that same plant. Early senescence caused by wind has also been previously recorded in cocklebur plants (Salisbury, 1963).

Wind did not interact with either true leaf or variety. However, the main effect of true leaf was significant, indicating that leaf characteristics differed among leaf cohorts. Outer canopy leaves tend to be thicker than inner leaves due to greater light availability (Witkowski and Lamont, 1991). Similar trends emerged during the greenhouse and hoophouse experiments. At harvest, the third true leaf was generally smaller and tended to be lower towards the soil, light levels were quite possibly reduced compared to younger emerging leaves. True leaf 5 had the lowest SLA and was exposed to wind between 11 and 13 days, although not always fully emerged. True leaf number was correlated to leaf age and days of wind exposure, but did not result in a wind interaction. Leaf age could not be analyzed due to the small sample size generated at any given wind speed, wind duration, and wind run.

Physical leaf characteristics explain some of the varietal differences seen during the greenhouse experiments. ‘Lollo Rossa’ tended to have more vascular tissue throughout the lamina portion of the leaf than ‘Red Saladbowl’ regardless of wind treatment. Increased vascular tissue would explain why market mass and SLM_f were greater in ‘Lollo Rossa’. However, neither leaf characteristic nor days of exposure to mechanical stimulation generated a significant wind interaction. Overall, in the greenhouse experiments ‘Red Saladbowl’ variety had a greater lamina LDMC and whole leaf LDMC, and lower lamina SLA. These characteristics indicate ‘Red Saladbowl’ has a thicker leaf regardless of treatment compared to ‘Lollo Rossa’, while overall market mass was greater in ‘Lollo Rossa’.

LDMC and SLM correlation

LDMC is considered an accurate measurement of plant characteristics because it does not rely on leaf thickness as does SLA (Wilson et al., 1999). Fresh mass measured with disc punches of leaf lamina during initial experiments was difficult due to small leaf mass and rapid water loss.

SLA was strongly negatively correlated to LDMC at a value of r = - 0.74 (Vile, 2005). During both the hoophouse and single replicate container experiments, correlation between SLM and LDMC was $R^2 = 0.86$. During the hoophouse experiment, SLM and LDMC were not significantly different from the control, but on average approximately 9% and 13% less respectively (Table 2.2B). During the single replicate container experiment, SLM of leaf lamina responded to wind run more than LDMC. During both the tray and subset container greenhouse experiments, R^2 was ~ 0.75. In contrast to the single replicate container experiment, all wind combinations generated whole leaf LDMC significantly less than the control during the subset container experiments. Measurement of SLA during the hoophouse and greenhouse experiments supports the suggestion that SLA is susceptible to spatial and temporal variation (Wilson et al., 1999).

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TABLES

Table 2.1 Wind run for different combinations of wind duration and wind speed that were used during all greenhouse experiments and the 2017 hoophouse experiment.

Wind Speed[z]	Duration[y] 10	Duration 20	Duration 30
2.2	1.3[x]	2.6	4.0
2.3	1.4	2.8	4.1
-	-	-	-
4.3	-	-	7.7
4.4	2.6	5.3	7.9
4.5	2.7	5.4	8.1
4.6	2.8	5.5	-
-	-	-	-
6.5	3.9	7.8	11.7
6.6	4.0	7.9	12.0
6.7	4.0	8.0	12.1

[z] Three wind speeds were chosen: 2.2, 4.5, 6.6 m s^{-1}. For simplicity, these are referred to as 2, 4, and 6 m s^{-1}, respectively, in this paper.

[y] Three wind durations (daily application of wind) were chosen: 10, 20, and 30 minutes, with half the duration in the morning and the other half in late afternoon.

[x] These combinations of wind speed and wind duration resulted in six daily wind runs (approximately 1.3, 2.7, 4.0, 5.4, 7.9, and 12.0 km d^{-1}) plus a control with zero wind speed and zero wind duration. Similar shadings indicate comparative wind runs across different combinations of wind speeds and wind durations.

Table 2.2. ANOVA and mean comparison results from hoophouse experiments that were conducted under representative production conditions.

2.2A ANOVA results.

			P-value[z]			
Experiment[y] & ANOVA factors	Num df[x]	Den df[x]	SLA_L[w]	SLM_f[w]	LDMC[w]	Market[w]
HH 2016[v]						
Speed	2	1	0.798	0.581	0.554	-
Variety[u]	1	6	0.242	0.938	0.183	-
Speed x Var	2	6	0.857	0.622	0.912	-
HH 2017[t]						
ANOVA with Duration_Speed as wind treatment						
Duration_Speed	5	7	0.081	**0.022**	-	**0.022**
True Leaf[s]	2	20	**<0.001**	**<0.001**	-	**<0.001**
D_S x True L	10	20	0.648	0.215	-	0.215
ANOVA with Wind Run as wind treatment						
Wind Run	4	6	0.212	**0.026**	-	**0.026**
True Leaf	2	18	**<0.001**	**<0.001**	-	**<0.001**
WR x True L	8	18	0.939	0.164	-	0.164

2.2B Least square mean values, standard errors of mean, and mean comparisons.

Experiment[y]	Duration (min)	Speed ($m\ s^{-1}$)	SLA_L[w] ($mm^2\ mg^{-1}$)	SLM_f[w] ($mg\ mm^{-2}$)	LDMC[w] (%)
HH 2016[v]	0	0	46 ± 3 a[r]	0.21 ± 0.00 a	11.0 ± 0.5 a
	10	1	50 ± 4 a	0.22 ± 0.01 a	09.9 ± 0.7 a
	10	4	52 ± 4 a	0.22 ± 0.01 a	09.6 ± 0.6 a
HH 2017[t]	0_M	0_M	73 ± 1 a	-	-
	0	0	71 ± 2 a	-	-
	10	2	78 ± 2 a	-	-
	10	6	78 ± 2 a	-	-
	30	2	62 ± 2 a	-	-
	30	6	68 ± 2 a	-	-

[z] Bold P values indicate significant at $P \leq 0.05$.

[y] ANOVA and mean comparison results are given for two hoophouse experiments, one conducted during the 2016 production season (HH 2016) and one during the 2017 production season (HH 2017).

[x] Num df and Den df indicate numerator and denominator degrees of freedom, respectively.

[w] SLA_L is lamina specific leaf area, SLM_f is lamina fresh specific leaf mass, LDMC is leaf dry matter content, and MARKET is whole leaf fresh mass.

[v] Hoophouse (HH) 2016 experiment included one control (i.e. no wind) treatment and wind treatments of one wind duration of 10 minutes with either wind speed of 1 $m\ s^{-1}$ or wind speed of 4 $m\ s^{-1}$.

[u] *Latuca sativa* 'Green Saladbowl' and 'Prize' varieties. Five plants were sampled in each of 3 replicate sets of study plots.

[t] HH 2017 included two controls, one with (0_M) and one without (0) a mylar barrier around study plants. Wind treatments included four combinations of wind duration (min) and wind speed ($m\ s^{-1}$): Duration_Speed combinations of 10_2, 10_6, 30_2, and 30_6. Corresponding wind runs were 1.3, 4.0, and 12.0 $km\ d^{-1}$. Only *Latuca sativa* 'Red Saladbowl' variety was used. Ten plants were sampled in each of 2 sets of replicate study plots.

[s] The third, fourth, and fifth true leaves that were formed, True Leaf 3, 4, and 5 respectively, were sampled during the experiment.

[r] Means within a column for each experiment that have the same letter are not significantly different.

Table 2.3. ANOVA and mean comparison results from high density greenhouse tray experiments that were conducted under representative production conditions.

2.3A ANOVA results.

			P-value[z]			
Experiment[y] & ANOVA factors	Num df[x]	Den df[x]	SLA_L[w]	SLM_f[w]	LDMC[w]	Market[w]
GH Tray[u]						
ANOVA with Duration_Speed as treatment						
Variety[t]	1	2	**0.008**	0.078	**0.015**	0.487
Duration_Speed	9	36	0.436	0.088	0.247	0.610
Var x D_S	9	36	0.970	0.860	0.988	0.855
ANOVA with Wind Run as treatment						
Variety	1	2	**0.007**	**0.035**	**0.015**	0.698
Wind Run	6	24	0.348	0.117	0.351	0.214
Var x WR	6	24	0.920	0.376	0.973	0.894

2.3B Least square mean values, standard errors of mean, and mean comparisons.

Experiment[y]	Duration (min)	Speed ($m\ s^{-1}$)	SLA_L[w] ($mm^2\ mg^{-1}$)	SLM_f[w] ($mg\ mm^{-2}$)	LDMC[w] (%)	MARKET[w] (mg)
GH Tray[u]	0	0	143 ± 4 a[s]	277 ± 6.2 a	5.7 ± 0.2 a	337 ± 13 a
	10	2	123 ± 4 a	263 ± 5.6 a	6.4 ± 0.2 a	303 ± 12 a
	10	4	123 ± 4 a	249 ± 5.4 a	6.2 ± 0.2 a	309 ± 14 a
	10	6	128 ± 4 a	245 ± 4.7 a	6.2 ± 0.2 a	279 ± 11 a
	20	2	128 ± 5 a	301 ± 5.7 a	6.3 ± 0.2 a	315 ± 13 a
	20	4	126 ± 4 a	301 ± 7.3 a	6.2 ± 0.2 a	396 ± 20 a
	20	6	132 ± 5 a	278 ± 6.0 a	6.5 ± 0.2 a	284 ± 12 a
	30	2	130 ± 4 a	290 ± 7.3 a	5.7 ± 0.2 a	331 ± 17 a
	30	4	141 ± 4 a	284 ± 7.2 a	5.6 ± 0.2 a	360 ± 18 a
	30	6	131 ± 5 a	264 ± 8.5 a	5.9 ± 0.2 a	285 ± 14 a

[z] Bold P values indicate significant at $P \leq 0.05$.

[y] Mean comparison results are given for the greenhouse high density tray experiment.

[x] Num df and Den df indicate numerator and denominator degrees of freedom, respectively.

[w] SLA_L and SLM_f denote lamina specific leaf area and fresh lamina specific leaf mass, respectively, LDMC denote lamina leaf dry matter content, and MARKET is whole leaf fresh mass.

[u] GH Tray experiment included 3 replicate control plots, and wind treatments included nine combinations of wind duration (min) and wind speed ($m\ s^{-1}$): Duration_Speed combinations of 10_2, 10_4, 10_6, 20_2, 20_4, 20_6, 30_2, 30_4, 30_6. Corresponding wind runs were 1.3, 2.7, 4.0, 5.4, 7.9, and 12.0 $km\ d^{-1}$

[t] *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' varieties. 10 plants were sampled in each of 3 replicate sets of study plots.

[s] Means within a column for each experiment that have the same letter are not significantly different.

Table 2.4. ANOVA results from low density greenhouse container experiments that were conducted under representative production conditions.

			P-value[z]		
ANOVA[y] factors	Num df[x]	Den df[x]	SLA_L[w]	LDMC[w]	Market[w]
All GH[v]					
ANOVA with Duration_Speed as treatment					
Variety[u]	1	14	**<0.001**	**0.010**	**<0.001**
Duration_Speed	9	192	**<0.001**	**0.022**	0.134
True Leaf[t]	2	319	**<0.001**	**<0.001**	**<0.001**
Var x D_S	9	192	0.892	0.952	0.740
Var x True L	2	319	**<0.001**	**<0.001**	**<0.001**
D_S x True L	18	319	0.688	0.454	0.947
Var x D_S x True L	18	319	0.998	0.591	0.935
ANOVA with Wind Run as treatment					
Variety	1	14	**<0.001**	**0.009**	**<0.001**
Wind Run	6	132	**<0.001**	**0.022**	0.147
True Leaf	2	223	**<0.001**	**<0.001**	**<0.001**
Var x WR	6	132	0.754	0.842	0.964
Var x True L	2	223	**<0.001**	**<0.001**	**<0.001**
WR x True L	12	223	0.734	0.291	0.898
Var x WR x True L	12	223	0.985	0.354	0.842

[z] Bold P values indicate significant at $P \leq 0.05$.

[y] ANOVA results are given for the greenhouse low density container experiments.

[x] Num df and Den df indicate numerator and denominator degrees of freedom, respectively.

[w] SLA_L denote lamina specific leaf area. LDMC is lamina leaf dry matter content. MARKET is whole leaf fresh mass.

[v] All GH includes the five replicate greenhouse container experiments that included 3 replicate control plots, and wind treatments included nine combinations of wind duration (min) and wind speed (m s^{-1}): Duration_Speed combinations of 10_2, 10_4, 10_6, 20_2, 20_4, 20_6, 30_2, 30_4, 30_6. Corresponding wind runs were 1.3, 2.7, 4.0, 5.4, 7.9, and 12.0 km d^{-1}

[u] *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' varieties. 10 plants were sampled in each of 3 replicate sets of study plots.

[t] The third, fourth, and fifth true leaves that were formed, True Leaf 3, 4, and 5 respectively, were sampled during the experiment.

Table 2.5. ANOVA and results from low density greenhouse container experiments.

			P-value[z]				
ANOVA[y] factors	Num df[x]	Den df[x]	SLA_M[w]	SLA_V[w]	SLM_f[w]	LDMC[w]	Market area[w]
GH subset[v]							
ANOVA with Duration_Speed as treatment							
Variety	1	5	0.550	0.151	**<0.001**	0.050	0.678
Duration_Speed	4	40	**<0.001**	**<0.001**	0.304	**<0.001**	**<0.001**
Var x D_S	4	40	0.161	0.143	0.573	0.166	0.250
ANOVA with Wind Run as treatment							
Variety	1	5	0.536	0.149	**<0.001**	0.051	0.678
Wind Run	3	30	**<0.001**	**<0.001**	0.185	**<0.001**	**<0.001**
Var x WR	3	30	0.060	**0.020**	0.393	0.054	0.297

[z] Bold P values indicate significant at $P \leq 0.05$.

[y] ANOVA results are given for the greenhouse low density container experiments.

[x] Num df and Den df indicate numerator and denominator degrees of freedom, respectively.

[w] SLA_M, and SLA_V denote specific leaf area of market whole leaf and vascular leaf parts, respectively. SLM_f is fresh lamina specific leaf mass, and LDMC denote lamina leaf dry matter content. Market Area is whole leaf fresh area.

[v] GH subset includes two of the replicate greenhouse experiments when additional leaf measurements were made. The experiment included 3 replicate control plots and a subset of wind speed and wind duration: Duration_Speed to 10_2, 10_6, 30_2, and 30_6 wind duration and wind speed combinations and wind run included 1.3, 4.0, and 12.0 km d^{-1}.

[u] *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' varieties. 10 plants were sampled in each of 3 replicate sets of study plots.

[t] Means within a column for each experiment that have the same letter are not significantly different.

Table 2.6. Least square mean values, standard errors of mean, and mean comparisons results from low density greenhouse container experiments.

Experiment[z]	Duration (min)	Speed ($m\ s^{-1}$)	MARKET[y] (mg)
All GH[x]	0	0	925 ± 14 a[w]
	10	2	911 ± 13 a
	10	4	846 ± 14 a
	10	6	901 ± 13 a
	20	2	885 ± 13 a
	20	4	868 ± 13 a
	20	6	877 ± 13 a
	30	2	900 ± 13 a
	30	4	851 ± 13 a
	30	6	888 ± 13 a

[z] Mean comparison results are given for the greenhouse low density container experiments.
[y] MARKET is whole leaf fresh mass.
[x] All GH includes the five replicate greenhouse container experiments, and each experiment included 3 replicate control plots, and wind treatments included nine combinations of wind duration (min) and wind speed ($m\ s^{-1}$): Duration_Speed combinations of 10_2, 10_4, 10_6, 20_2, 20_4, 20_6, 30_2, 30_4, 30_6. Corresponding wind runs were 1.3, 2.7, 4.0, 5.4, 7.9, and 12.0 km d^{-1}
[w] Means within a column for each experiment that have the same letter are not significantly different.

Table 2.7. Least square mean values, standard errors of mean, and mean comparisons results from low density greenhouse container experiments.

Experiment[z]	Duration (min)	Speed ($m\ s^{-1}$)	Market Area[y] (mm^2)
GH subset[x]	0	0	3110 ± 60 a[w]
	10	2	3324 ± 68 ab
	10	6	3533 ± 82 b
	30	2	3352 ± 81 ab
	30	6	3376 ± 75 ab

[z] Mean comparison results are given for the greenhouse low density container experiments.
[y] Market Area is whole leaf fresh area.
[x] GH subset includes two of the replicate greenhouse experiments when additional leaf measurements were made. The experiment included 3 replicate control plots and a subset of wind speed and wind duration: Duration_Speed to 10_2, 10_6, 30_2, and 30_6 wind duration and wind speed combinations and wind run included 1.3, 4.0, and 12.0 km d^{-1}.
[w] Means within a column for each experiment that have the same letter are not significantly different.

FIGURES

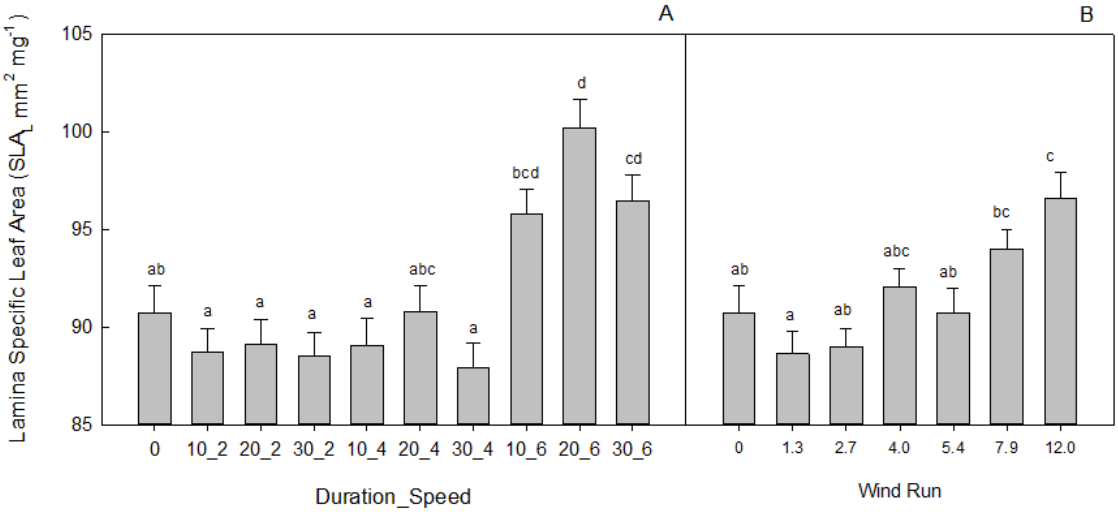

Fig. 2.1. Lamina specific leaf area for *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' plants exposed to wind treatment during greenhouse container experiments (A) Duration_Speed wind treatment combinations, (B) Wind Run treatments. Bars indicate standard errors (n = 10). Means with the same letter were not significantly different ($P \leq 0.05$).

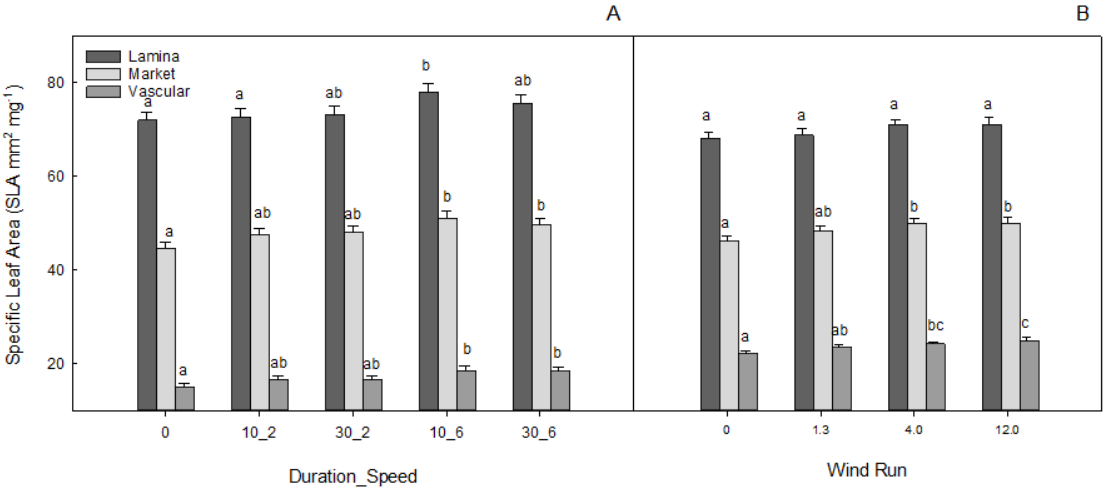

Fig. 2.2. Specific leaf area of three leaf parts to determine where the response to wind occurs. Lamina, whole leaf market, and vascular leaf tissue of *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' plants exposed to wind treatment during subset greenhouse container experiments. (A) Duration_Speed wind treatment combinations, (B) Wind Run treatments. Bars indicate standard errors (n = 10). Means with the same letter within each tissue type were not significantly different ($P \leq 0.05$).

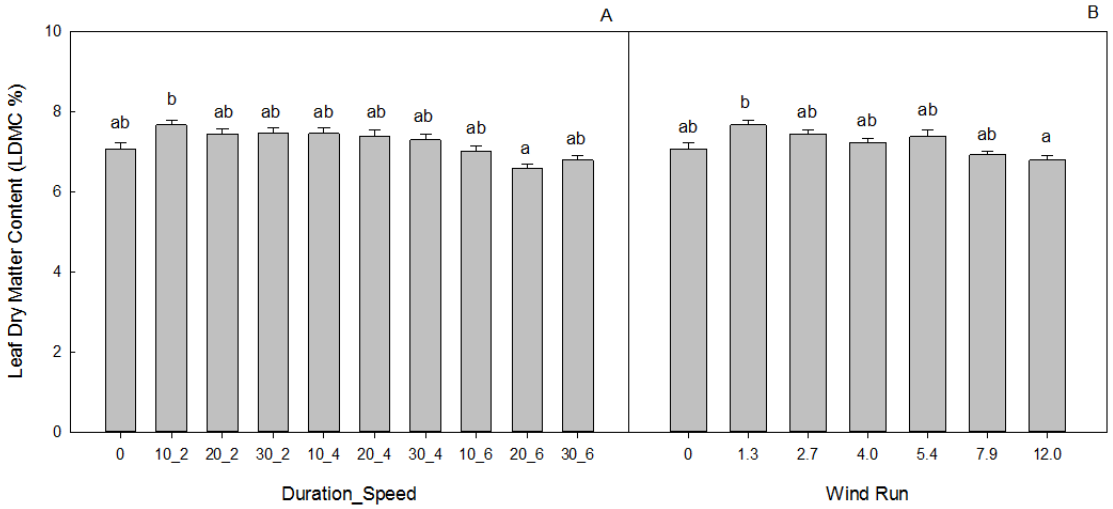

Fig. 2.3. Lamina leaf dry matter content of *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' plants exposed to wind treatment during a single replicate greenhouse container experiment. (A) Duration_Speed wind treatment combinations, (B) Wind Run treatment. Bars indicate standard errors (n = 10). Means with the same letter were not significantly different ($P \leq 0.05$).

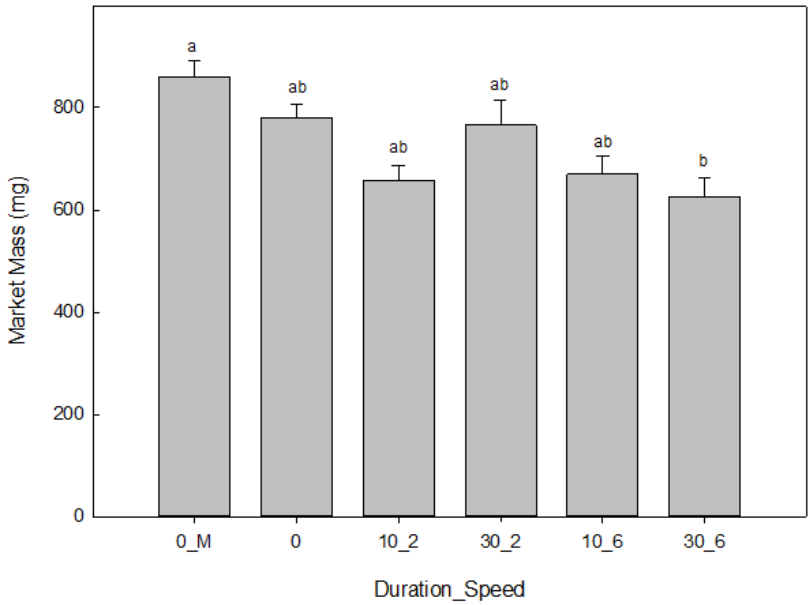

Fig. 2.4. Whole leaf market mass of wind exposed leaves of *Latuca sativa* 'Red Saladbowl' during high density hoophouse experiment. Duration_Speed wind treatment combinations include two controls; one with a mylar barrier to eliminate leaf movement (0_M) and the other without a barrier to mimic natural conditions within the hoophouse (0). Bars indicate standard errors (n = 10). Means with the same letter were not significantly different ($P \leq 0.05$).

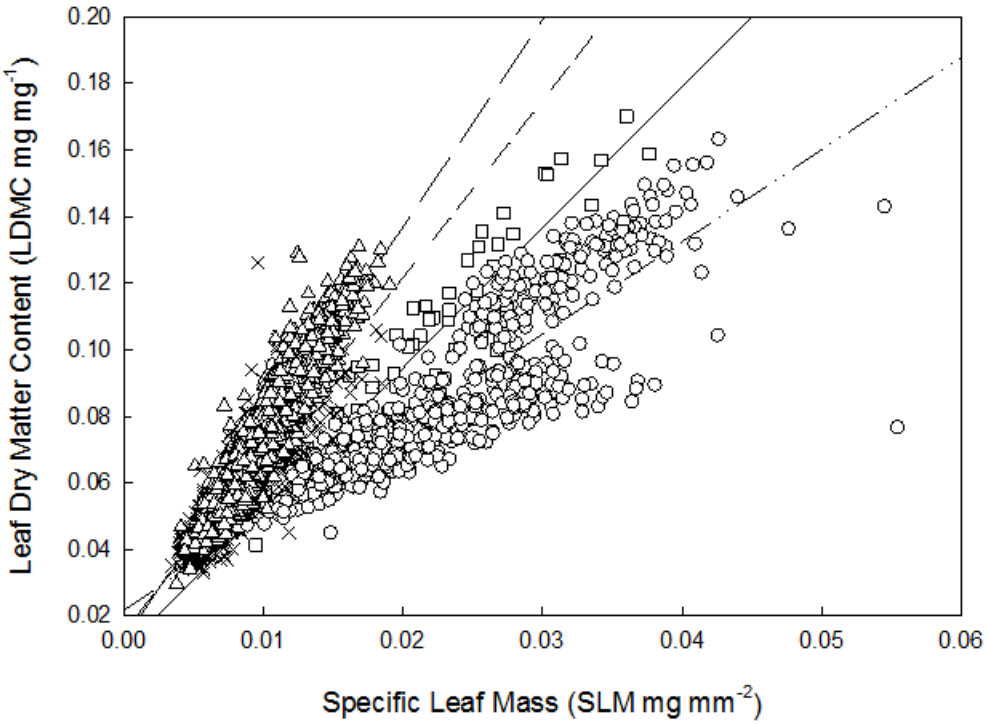

Fig. 2.5. Linear regression relationship between measured leaf dry matter content (LDMC, mg mg^{-1}) and specific leaf mass (SLM, mg mm^{-1}), with linear regression of lettuce grown in the high density hoophouse (HH, □ ——) and greenhouse experiment (TRAY, x _ _ _ _), and low density greenhouse experiments (GH2, ∆ ——; GH_SUBSET, ○ —··—).

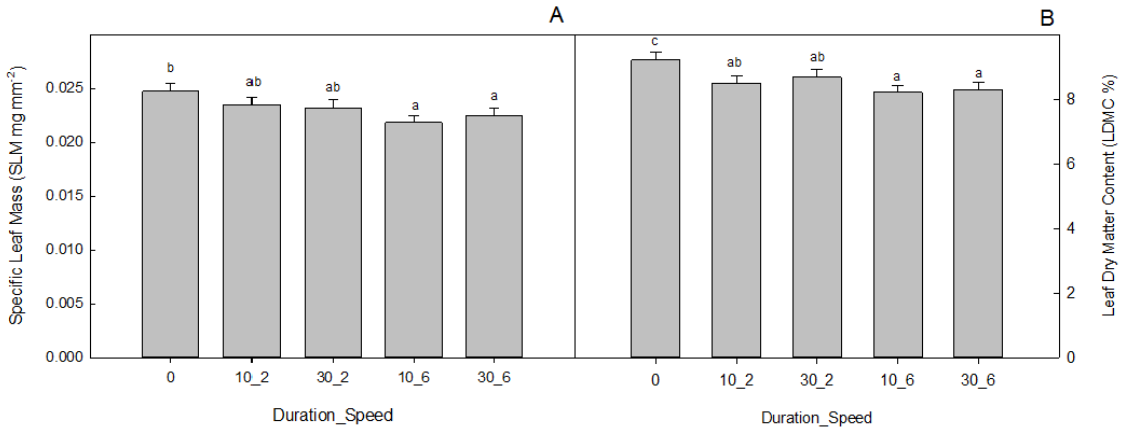

Fig. 2.6. Comparison of specific leaf mass (SLM) and leaf dry matter content (LDMC) of *Latuca sativa* 'Red Saladbowl' and 'Lollo Rossa' plants exposed to wind treatment during subset container greenhouse experiments. (A) SLM of Duration_Speed wind treatment combinations, (B) LDMC of Duration_Speed wind treatment combinations. Bars indicate standard errors (n = 10). Means with the same letter were not significantly different ($P \leq 0.05$).

Chapter 3: Enhancing production of warm and cool season crops using hoophouses

ABSTRACT

The use of hoophouses for vegetable production is increasing in high deserts due to the potential benefits of greater yield and quality as well as of year round production and season extension. If hoophouses in the high desert environment can be utilized to provide optimal environmental conditions for year round growth, then local growers and consumers will benefit from the knowledge gained from the current experiments. To document potential benefits, hoophouses and field plots were utilized to compare yield of warm season and cool season crops. During the summer 2015 experiment, heirloom tomato and watermelon varieties were grown to investigate total, weekly, and cumulative yield under hoophouses and field grown conditions. The result was an overall increase in total yield in hoophouses over field plots and a reduction in marketable fruit loss due to mammal damage. Additionally, three mulch treatments were implemented to determine if the use of mulch compared to bare ground would increase yield in either of the growing environments. Watermelon plants benefited the most from compost mulch treatment in both the hoophouses and field plots compared to bare ground. During the winter 2015-2016 experiment, leafy greens and root crops were grown at four different successive planting dates. Almost complete crop failure occurred in the field plots, resulting in greater yield in hoophouses for all crops. A planting date of early October generated continued yield throughout the winter months for leafy greens and a head start on spring harvest compared to successive plantings at three, six, or nine weeks later. In contrast, crops that were only harvested once (i.e. root crops, beet greens, and Claytonia) had variable responses in total yield to successive plantings. During the summer 2016 experiment, heirloom watermelons and tomatoes were grown in hoophouses and field plots to test season extension. Two planting dates, one of

early-March and the other in early-June, were used. Complete crop failure of the early planting treatment occurred in the field plots, whereas hoophouses had near 100% survival. The early successive planting had greater total, weekly, and cumulative yield for tomato plants. However, only cumulative yield was greater in the early planting treatment than later planting treatment for watermelons. Two vascular wilt fungal diseases were present in the hoophouses and caused greater plant loss in the early planting treatment than later planting treatment. These experiments demonstrate that hoophouses generally outperform field plots for the studied crops, year round production of crops is feasible, and season extension for warm season crops is beneficial.

INTRODUCTION

Hoophouses are designed to extend the season and protect crops from potentially damaging weather events. The natural diurnal temperature variation in high desert climates can be utilized with the use of hoophouses to optimize growth. During heat of summer, hoophouses can provide protection from direct sun through the use of light-diffusing film and shade cloth to reduce sunscald to fruit (Hunter et al., 2010) or mulch to retain soil moisture and reduce soil temperature. Hoophouses also increase day time temperature during the winter, which, in sunny climates such as the high desert, can help bring the daily internal temperature into the optimum range for that crop (Gent, 2002). Temperature rapidly rises inside a hoophouse in the sun when outside air temperatures on average are too low for optimal plant growth during transitional seasons (Wien, 2009). Early season sunny, warm day time temperatures are ideal for starting warm season crops, and hoophouses can protect these crops from early and late season frost.

Hoophouses have proven effective at increasing quality and quantity of fruit and vegetables compared to field grown crops (Lamont et al., 2003; Wittwer and Castilla, 1995; Rogers and Wszelaki, 2012). Hoophouses also reduce the potential for disease and pest issues when proper cultural practices and crop rotation techniques are used (Lamont, 2005; Blomgren and Frisch, 2007). Hoophouses are effective in reducing pests that are commonly found on watermelon plants, such as aphids, thrips, and other pests that are hosts for plant disease (Jett, 2006). Hoophouses also provide protection against excessive moisture and generate warmer temperatures, which prevent certain physiological and environmental tomato disorders such as fruit cracking, blossom end rot, and cat-facing (Dorais et al., 2001). Organic, locally grown heirloom varieties have a high market value. However, heirloom plants are generally not disease resistant, which makes them more prone to misshapen or unmarketable fruit. Therefore, hoophouses can provide ideal growing conditions for tomato and watermelon plants by manipulating cultural practices appropriately (Rogers and Wszelaki, 2012). Furthermore, sensory

scores for hoophouse grown tomatoes was higher for sweetness, flavor, texture, and taste compared to field grown tomatoes (Krizek et al., 2006).

Altering a crop's microclimate to accelerate growth, extend the growing season, and increase yield is an important consideration when choosing crops and other means to optimize the environment. Mulch treatments have been employed to reduce weed pressure and alter root zone temperature. Varying forms of mulch protect the soil by decreasing soil water loss as well as reducing temperature and soil moisture fluctuation (Kader et al., 2017). White on black plastic mulch is best utilized on summer crops for its cooling potential on soil and increased yield (Lamont, 2005, Hana et al., 1997). On the other hand, organic mulches encourage microbial activity, which aids in the breakdown of material and generates a slow release of nutrients for plants (Chantigny, 2003).

Hoophouses provide additional protection for winter grown crops such as leafy greens and root crops. Winter greens have been successfully grown in temperate climates (Gent, 2002), as well as beetroot and carrot (Coleman, 1992, 2009). Greens such as spinach and arugula can be harvested multiple times throughout the winter months (Hunter et al., 2012), making it an ideal crop for a repeated marketable harvest. Soluble sugars increase in spinach when exposed to cold temperatures resulting in a higher quality crop (Yoon et al., 2017). Successive plantings of carrots in October for February harvest and late December for harvest in May in New England has been a successful and reliable crop (Coleman, 2009). Beet root grown over winter in hoophouses has made it to market in spring 6-8 weeks prior to field grown root crops (Coleman, 2009). Although knowledge on winter hoophouse grown produce in the high desert is limited, hoophouses likely provide potentially productive growing seasons for a wide range of potentially successful crops.

The increased demand for local, organically grown fruit and vegetables, especially in the off-season, will increase profitability when season extension is utilized. High desert extreme diurnal temperature variations greatly limit the growing season for high quality warm season

vegetable crops such as tomato and watermelon if additional protection is not provided. Tomatoes are typically planted outdoors in mid- June in northern Nevada (personal communication), but hoophouse extension for tomato plants has been pushed into mid-March with harvest beginning in early July (Hunter et al., 2010; Hunter et al., 2012; Wells and Loy, 1993). Muskmelon fruit matured 2 – 3 weeks earlier in hoophouses with the addition of row covers, and provided greater fruit yield, overall, than field grown melons (Waterer, 2003). Mini watermelons (≤ 6 lbs) are increasingly popular, especially heirloom type varieties that can be packed in a hoophouse easily with trellising (Jett, 2006). Cloth row covers are recommended for early season transplants of cold sensitive plants, which can increase temperatures by 2-6 °C (Ward and Bomford, 2013; Emmert, 1956; Waggoner, 1958). Organically grown heirloom crops such as tomato and watermelon are a high quality crop with high market demand, especially if placed in the market early in the season.

As year round demand for locally grown produce increases, more knowledge on methods to achieve a consistent year round supply is necessary. Hoophouses are a viable way to increase yield and extend into seasonal gaps that fill high quality produce demands. Three experiments were conducted at the Main Station Field Lab: two summer experiments that utilized heirloom tomato and watermelon varieties, and one winter experiment that grew heirloom leafy green and root crops. Organic practices were implemented during all studies. The summer 2015 experiment investigated total, weekly, and cumulative yield of heirloom tomato and watermelon plants in the high desert under hoophouse and field conditions. Additionally, three different mulch types were compared to a control to determine if any mulch would increase yield in either the hoophouses or field plots or among fruit type. The winter experiment was conducted during the 2015-2016 growing season. Spinach, arugula, and kale are all cold tolerant crops that provide multiple harvests throughout the growing season. In addition, two carrot varieties, beet root, beet greens, and Claytonia were grown as single harvest crops. Different planting dates were tested to

determine how four successive seeding dates affect days to harvest as well as total, weekly, and cumulative yield among varieties and in hoophouse and field grown plants. The third experiment during the summer of 2016 tested season extension of tomato and watermelon varieties at two different planting dates to determine if total, weekly, and cumulative yield differed among planting dates, varieties, and between hoophouse and field grown plants. Additionally, days to first harvest was determined between planting dates for each variety.

MATERIALS AND METHODS

Four hoophouses and two field plots were used for growing produce at the Main Station Field Lab, Nevada Agricultural Experiment Station, University of Nevada, Reno (1373 m elevation, 90 day growing season). All hoophouses were 20 by 36 feet, oriented north-south because of the typical direction of prevailing winds and arranged from west to east as hoophouse (HH) 1, field plot (FP) 1, HH2, HH3, FP2, and HH4, respectively (Fig. A.6). Hoophouses were permanent structures with side walls that rose vertically 5.5 feet from the ground before arching to a peak height of 10 feet. Ventilation was provided by manually rolling up the sides from the top of the side wall at 20 inches to 66 inches, as well as opening entry doors and roof vents on both end walls. Side walls and roof were covered with Solarig woven poly 172 (Solarig Co.). Each hoophouse and field plot was set up as replicate plots, each with four mounded soil (raised) beds 25 by 2 feet (Fig. A.7), which were amended with compost soil (Oxborrow Trucking & Landscape Materials; Reno, NV) prior to all new experiments. Soil was tested in late summer 2015 through the University of Nevada Cooperative Extension. Results indicated soil texture on site was a sandy loam with pH 8, and free lime present. Irrigation was applied through two drip tapes (Toro Micro-Irrigation, The Toro Company) with 8-inch emitter spacing placed along the edges of each raised beds, approximately a foot apart, and regulated by timers programed using Hunter NODE-200 with four DC solenoids (Hunter Industries, San Marcos, CA).

Three seasonal experiments were conducted that were laid out in an unbalanced split-split-split-plot design. The first consisted of a warm season experiment in summer 2015. The primary focus was varietal trials of tomato and watermelon plants and comparison of different mulch treatments. Second was a cool season experiment conducted in winter 2015 – 2016 that focused on varietal trials and successive plantings of leaf and root crops. Third included a warm season experiment that was conducted during summer 2016 and examined season extension of tomato and watermelon plant varieties.

Summer 2015 Experiment

The summer 2015 experiment was conducted from June – September 2015 using heirloom plant varieties. Five tomato varieties, 'Brandywine', 'Cherokee Purple', 'Cour di Bue', 'Mewaldt Cherry', and 'Mewaldt Roma', and two watermelon varieties, 'Golden Midget' and 'Sugar Baby', were grown during the summer 2015 experiment. Transplant into hoophouses and field plots occurred in mid-June. Each of the four rows received one plant of each variety for a total of seven plants per raised bed, resulting in sixteen plants per variety across all hoophouses and eight plants per variety across all field plots. Spacing between plants was 3.5 feet for tomatoes and watermelons. Each raised bed received a different mulch treatment that included bare ground as the control, compost mulch, wood chip mulch, and white on black plastic mulch, installed in mid-July (Fig. A.8). Drip tape for irrigation was placed under the mulch treatment. The variety location and mulch treatments were randomly assigned to each raised bed within a single plot. The experimental design was a randomized incomplete split-split-split plot with the whole plot as the growth environment (hoophouse versus field plot), the individual hoophouses and field plots serving as replicates, four levels of mulch treatment as the split plot treatment, and five tomato varieties and two watermelon varieties as the split-split plot factor. Harvest date was treated as the smallest experimental treatment, or split-split-split plot factor, with seven levels.

All plants were trellised using a T-post design, with a horizontal string at approximately six feet above the ground and vertical strings to support the main stem by weaving the stem up the string. Additional string was used to support branching stems and vines (Fig. A.9). Tomato suckers were pruned on all varieties when still less than two inches, and lower leaves were removed to increase airflow around the plant. On the watermelons, secondary vines not bearing blooms were pruned. As watermelon fruit developed, mesh bags were used to support the fruit and tied to the support wire (Fig. A.10) (Jett, 2006). Water application was irregular due to irrigation timer programing issues, and more water was applied than necessary. Irrigation timers were programed properly in early September, and water was applied for 15 minutes per day through final harvest, which was sufficient to maintain fully turgid plants.

First crop harvest began on August 8th, and final harvest occurred September 17th. Ripe tomatoes and watermelons were picked 2-3 times per week, but all marketable harvest per plant within a single week was pooled for a weekly harvest amount. Marketable, ripe fruit was pulled, weighed, and recorded per plant. Non-marketable rotten or pest damaged fruit was also weighed and recorded by plant where possible, although due to rodents moving fruit, it was not always possible to determine what plant lost fruit. Chicken wire was installed over roll-up sides to prevent rodents from entering the hoophouses in late August. Because the field plots were more difficult to protect, chicken wire was installed around the perimeter of the plots to a height of two feet from ground level.

Plant loss and reason for decline was recorded throughout the growing season as some plants progressively declined in health. Soil samples were sent to A & L Western Agricultural Laboratories for soil fertility analysis, and plant samples were sent to the Plant Pathology Laboratory, Nevada Department of Agriculture for diagnostics in mid-July. Soil analyses indicated possible iron, zinc, and manganese deficiencies, due to soil alkalinity, and soil was amended with organic slow release fertilizer (Jobe's Organics Granular Fertilizer; 2-7-4). Plant

analyses did not identify any pathogens or disease, which indicated that the observed leaf roll and discoloration was due to environmental or climatic causes. Plants with irreversible damage were pulled August 31, approximately 2.5 weeks before final harvest.

Winter 2015 – 2016 Experiment

Crops included in the winter experiment were four leafy greens (*Spinacia oleracea* 'Gazelle', *Eruca vesicaria spp. sativa* 'Roquette', *Brassica oleracea var. fimbriata* 'Dwarf Kale', *Claytonia perfoliata*), beets that are used for both greens and root crops (*Beta vulgaris* 'Baby Beat'), and two carrot varieties (*Daucus carota var. sativus* varieties 'Mokum' and 'Sugarsnax'). Leafy greens and root crops were directly sown in 6 x 24 inch areas within the raised bed (Fig. A.11), which resulted in two rows of seed within a 144 in^2 area. Four successive plantings were sown every three weeks beginning October 2nd adjacent to the previous successive planting of that variety; the last successive planting occurred December 4th. Each raised bed received all crop varieties and successive plantings. However, kale was only sown during the first successive planting in a 24 x 24 inch area, due to the size of the crops. Each raised bed had six kale plants. Additionally, only the first two successive plantings were sown in the field plots. Due to crop failure in field plots, subsequent successive plantings were omitted. Plants were thinned to the recommended spacing one week after emergence. The resulting experimental design was an incomplete split-split-split plot with the growing environment (hoophouse and field plot) as the whole plot, the individual hoophouses and field plots as the replicates, successive planting was the split plot with four levels, variety as the split-split plot, and harvest date as the split-split-split plot for those crops harvested over time. Varieties were randomly placed within each bed.

During harvest, crops were weighed for marketable fresh mass, bagged, and placed in a forced-air electric oven at 60 °C for at least 72 hours. Whole leaf or root dry matter was measured, and fresh and dry leaf masses were used to calculate leaf dry matter content (LDMC) of winter grown crops. Arugula, spinach, and kale in the hoophouses were repeatedly harvested

every two to four weeks throughout the winter beginning on December 1st. Approximately 70% of a plants leaf material was left in order to maintain productive growth and the advantage of growing 'cut and come again' crops. Beet greens, claytonia, and root crops were harvested once at final harvest. Two raised beds from each replicate plot were randomly selected and harvested in full on March 4th to prepare for incoming summer crops. The remaining rows were left in place for weekly harvest of greens and single harvest of all other crops on April 29th.

Field capacity was tested in early October and determined to be 21% water content for the raised beds at the Main Station Field Lab. Plots were irrigated as needed to maintain soils field capacity throughout this and future experiments. Winter crops received irrigation for 15 minutes (7.5 gallons per row) every other day until November 30th, after which irrigation was increased to 15 minutes every day to reduce drying of soil between watering and subsequent damage to root crops. Unfortunately, cold temperatures caused irrigation pipes to crack and fittings to come undone, after which raised bed were hand watered until the system could be repaired in February 2016.

Pest damage was an issue during the winter experiment, most prominently to kale and spinach crops. At harvest, percent either eaten or non-marketable due to aphid or spider mite damage was estimated or recorded for each crop variety and successive planting to determine how much yield was lost. Trap crops of radish and mustard were used, which can attract pests away from the main crops of interest to control aphids. Trap crops were sown in a 12 by 12 inch area in each raised bed in the hoophouses. When fully enveloped, the trap crops were cut at the base, bagged, and removed from the hoophouses. Spider mites were controlled using a strong spray of water during normal irrigation to wash mites from plant foliage. Squirrels were also an issue because they were able to burrow under the hoophouse structure at the irrigation access. The ground was dug out and chicken wire was installed with rocks to prevent further entrance into the hoophouses.

Summer 2016 Experiment

The summer 2016 experiment examined whether the growing season for tomato and watermelon plants can be extended by staggering planting dates on March 11th and June 11th. Three heirloom tomato varieties included 'Pink Berkeley Tie Dye', 'Black Cherry', and 'New Yorker'. The two heirloom watermelon varieties included 'Blacktail Mountain' and 'Sugar Baby'. Days to first harvest for tomato fruit as indicated from seed source, were mid 60 for 'Black Cherry' and 'New Yorker' and 65-75 for 'Pink Berkeley Tie Dye' and watermelons were 70-76. Tomato and watermelon seeds were sown in small pots in the greenhouse two weeks prior to being transplanted into plots. Two raised beds were randomly selected for the initial plant date, while the other two beds continued growing winter crops. Each 25 foot row consisted entirely either of the three tomato varieties or of the two watermelon varieties. Five plants of each variety were planted per row. Each of the five plants from a single variety were planted in a block within the raised bed, but location among varieties was randomly assigned. Tomato plants were placed every 20 inches and watermelons every 30 inches. The second planting in June was developed in the same manner. Total plant number per variety at each plant date was 20 plants in hoophouses and 10 plants in field plots (Fig A.12). The summer 2016 experiment was set up as a randomized incomplete split-split-split plot design with the growing environment as the whole plot, hoophouses and field plots as the replicates, two levels of planting treatments as the split plot, three tomato and two watermelon varieties as the split-split plot, and harvest date as the split-split-split plot with eleven levels.

Cloth row cover was used on individual raised beds suspended by wire hoops to increase plant protection any time daily temperatures were forecasted at or below 5 °C for the March planting date in both hoophouses and field plots. Frost was not an issue for the June plant date. All plants were trellised using a T-post and vertical string to support plants upward growth initially, but watermelon vines were unable to support the heavy fruit and fruit broke at the stem.

Thus, all watermelon vines bearing fruit were grown horizontally across the ground. Tomato suckers were pruned on all varieties, and lower leaves were removed to increase airflow around the plant. Summer crops were watered twice a day, in early morning and in late afternoon, for 20 minutes during peak summer heat to maintain field capacity.

Harvest occurred as needed to keep up with production, and all yield per plant was pooled to generate total weekly harvest. The first harvest occurred on June 19 and continued through August 28. Tomato yield was recorded for each individual plant, whereas watermelons were difficult to distinguish as vines intertwined, and thus yield was recorded per variety per raised bed and not by individual plants. Plant health was declining in mid-summer. Plant samples were sent to the Plant Pathology Laboratory, Nevada Department of Agriculture in late July for analysis. Results came back positive for *Fusarium* and *Verticillium* wilts in both watermelon and tomato plants. Plants that showed signs of wilt were pulled, bagged, and discarded. Plant pull date and location was recorded for tomatoes. Aphids were also a prominent feature in the hoophouses. M-Pede Insecticide Miticide Fungicide (Dow AgroSciences LLC) was applied at 2% solution to tomato and watermelon plants in the hoophouses according to the material safety data sheet every two weeks for three treatments beginning in early August.

Statistics

Analysis of two main response variables, weekly, and cumulative yield were conducted to address two questions: (1) whether varieties or plot type differed at any given week during the growing season; and (2) whether cumulative yield to date differed over time. A third response variable was also analyzed as total harvested yield by comparing cumulative yield on the final harvest date. Data were analyzed with and without plants that lost production during the growing season. Original data included zero production for plant loss, as it describes conditions experienced at the Main Station Field Lab. In addition, a best case scenario was also generated for all experiments, which reduced the influence from plant loss due to disease or other pest damage.

This second, “best-case” data set removed that plant from analysis at the corresponding date when it no longer was productive. The best case scenario generated means based on the number of plants in situ for both summer experiments, compared to the original data set that include plants with zero yield due to lack of production. For the winter experiment, the best case scenario assumed that the percent lost from pest damage was marketable and added that biomass back into the harvest on that date. All values altered using this method were reasonable compared to previous harvests on that particular successive planting and other plants in which damage had not occurred on that date. However, results from this analysis should be interpreted carefully. The best case scenario was used only for yield as the response variable, as it inflated cumulative yield.

Because of the incomplete split-split-split plot experimental design and the skewed data distribution from the large number of zeros in the data set (especially from field plots where plant establishment often did not occur), analysis with linear statistical models was not feasible. Thus, we sequentially analyzed the different factors in the experiments using Kruskal-Wallis non-parametric 1-way ANOVA in R software. Significant differences in means between different treatment types, varieties, plant date, and harvest date was determined using Conover’s test. Typically, the complete data set was first analyzed to determine whether field plot yield differed from hoophouse yield, i.e. if the whole-plot treatment factor of growth environment was significant. Second, the complete dataset was separated into a field plot subset and hoophouse subset and analyzed independently to determine if the split plot factor was significant. Subsequent ANOVAs to examine split-split plot and split-split-split plot factors further subset data into field plot watermelon, field plot tomato, hoophouse watermelon, hoophouse tomato, etc. Analysis of the winter experiment also included a subset of successive plantings when incomplete design was an issue; for example, kale only had one successive planting, and root crops, beet greens, and claytonia were only harvested once. Data was also subset by date to determine whether varietal differences occurred over time and which variety produced the most, produced first, and

produced longest. Subsetting to variety allowed us to determine how each variety differed between plots and how it produced over time.

Levels of significance were shown as the test statistic from a chi-squared distribution and $P \leq 0.05$. We note that non-parametric tests are typically more conservative than linear models that use normal or other distributions, and thus our analyses may include Type II errors. All means were reported from raw data with standard error. Non-parametric tests were used on all data due to zero-inflated data. Pairwise comparisons using Conover's test and the t-value of the student-t-distribution were applied to generate mean comparisons.

RESULTS

Summer 2015 Experiment

Because a major objective of the Summer 2015 experiment was to investigate if different mulch treatments affected yield of tomatoes and watermelons, we first analyzed datasets for significant mulch treatment effects. Total yield, which is total amount of marketable produce harvested over all harvest dates, did not differ significantly among the four mulch treatments when analyzed over all four hoophouse and both field plots and over all five tomato varieties and both watermelon varieties (Table 3.1A). Similarly, weekly yield (amount of marketable produce harvested over each week) and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week) did not differ significantly among mulch treatments (Table 3.1A). When data were divided into hoophouse and field plot subsets (but still over all five tomato varieties and both watermelon varieties, and over all harvest dates for weekly and cumulative yields), mulch treatments still were not significant for all yield measurements (Table 3.1B). Analyses of further subsets of data (subsets for each type of plot combined with each type of produce) did not yield any significant differences among mulch treatments for the three yield measurements for tomato crops (Table 3.1C). Total and weekly yield of watermelons in both hoophouses and field plots were also not significant among mulch types (Table 3.1C).

However, cumulative yield for watermelons in the hoophouses was significantly greater in the compost and wood treatment than no treatment. Additionally, cumulative yield for watermelons in the field plots was significantly greater in the compost treatment than wood and no treatment. Cumulative yield of plastic mulch was significantly greater than no treatment in the field plots. Thus, we conclude that the effect of mulch treatment on marketable yield was not significant in either the hoophouse or field plot treatments for tomatoes. However, watermelon cumulative yield was affected by mulch treatments in both the hoophouses and field plots, indicating that cumulative watermelon yield increased slightly faster with compost and wood mulches in hoophouses, but with compost and plastic mulches in field plots. All remaining analyses averaged over mulch treatments.

Over both varieties and all harvest dates, watermelon total yield was significantly greater for plants grown in hoophouses than in field plots by approximately 80% (Table 3.2A). However, when each watermelon variety was analyzed individually, neither variety had significantly greater total or weekly yield in hoophouses than field plots over all harvest dates (Table 3.2B). In contrast, cumulative yield over all harvest dates was significantly greater for plants grown in hoophouses than field plots by approximately 70% and 100% for Golden Midget and Sugar Baby varieties, respectively (Table 3.2B). Finally, total, cumulative, and weekly yields were not significantly different between varieties (results not shown).

Over all varieties and harvest dates, tomato total yield was significantly greater for plants grown in hoophouses than in field plots by approximately 65% (Table 3.3A). When analyzed by variety, total yield was significantly greater for Brandywine and Mewaldt Roma varieties grown in the hoophouses compared to field plots by almost 130% and 100%, respectively (Table 3.3B). For all other varieties, total yield did not significantly differ between hoophouses and field plots. Weekly yield over all harvest dates was significantly greater for plants grown in hoophouses than field plots for varieties Cour di Bue and Mewaldt Roma by almost 80% and 100%, respectively

(Table 3.3B). Cumulative yield was significantly greater for plants in the hoophouses than field plots by approximately 65%, 80% and 65% for Cour di Bue, Cherokee Purple, and Mewaldt Roma varieties, respectively (Table 3.3B). In contrast, weekly and cumulative yield of Brandywine and Mewaldt Cherry tomato plants was not significantly different between plants grown in the hoophouses versus field plots.

When data was further divided into hoophouse and field plot subsets, total yield was significantly different among varieties. For hoophouse grown tomatoes, total yield for Cour di Bue was significantly greater than Cherokee Purple, Mewaldt Cherry, and Mewaldt Roma varieties (Table 3.4). In addition, Brandywine had a significantly greater total yield for plants in the hoophouse than Mewaldt Roma plants. For plants grown in the field plots, varieties Cour di Bue and Mewaldt Cherry had significantly greater total yield than Mewaldt Roma plants. Unfortunately, analyses of weekly and cumulative yield among varieties within a plot type were confounded by the large number of zeros.

Each variety on each harvest date was also analyzed for significant differences in weekly and cumulative yield between plot type. Brandywine did not produce fruit until the second week of harvest in either plot type (Fig. 3.1). Weekly yield of Brandywine plants was significantly greater in field plots than in hoophouses on 14 Aug 2015 (Fig. 3.1A). In contrast, yield from hoophouse grown Brandywine plants was significantly greater than yield of field plot plants on the second to last harvest date of 11 Sept 2015. Brandywine cumulative yield in the field plots was significantly greater than hoophouses until 28 Aug 2015, with the exception of the initial harvest date 8 Aug 2015 (Fig. 3.1B). Brandywine cumulative yield was not significantly different between plot types again until final harvest on 17 Sept 2015, in which hoophouse cumulative yield was approximately 120% greater than field plots. Weekly yield of Cour di Bue in hoophouses was not significantly greater than field plots until 4 Sept and 11 Sept 2015, by approximately 530% and 180%, respectively (Fig. 3.2A). Cumulative yield of Cour di Bue plants

grown in the hoophouse was significantly greater than the field plots on 11 Sept 2015 by almost 90% (Fig. 3.2B). Weekly yield of Cherokee Purple was not significantly different between hoophouse and field plot grown plants on any individual harvest date (Fig. 3.3A). In contrast, cumulative yield of hoophouse grown plants was almost 700% greater in the hoophouses compared to field grown Cherokee Purple variety on 14 sept 2015 (Fig. 3.3B). Hoophouse grown Mewaldt Cherry weekly yield was significantly greater than field grown plants on the first harvest, but by the second harvest date, weekly harvest of field grown plants was significantly greater than hoophouse grown plants (Fig. 3.4A). On the final harvest date, weekly yield of hoophouse grown Mewaldt Cherry plants was approximately 80% greater than field grown plants (Fig. 3.4A). Cumulative yield of Mewaldt Cherry plants grown in the hoophouses was only significantly greater at the first harvest by approximately 450% (Fig. 3.4B). Weekly yield of Mewaldt Roma variety was not significantly different between hoophouses and field plots until the final two harvest dates, 11 Sept and 17 Sept 2015, by over 300% and 200%, respectively (Fig. 3.5A). In addition, cumulative yield was also significantly greater for hoophouse grown plants on those dates by almost 80% and 100%, respectively (Fig. 3.5B).

Plant loss from disease, insect, or other damage impacted some varieties more than others, and plot type was also a factor in percent plant loss. Plants were removed on August 31, 2015 from hoophouses and field plots if decline appeared irreversible. Plant removal did not occur in one mulch type more than another. Watermelon plants pulled were not recorded by variety, therefore only differences between plot type can be reported. Aphid damage was the main reason for early removal of watermelon plants in hoophouses. Six watermelon plants, or approximately 40%, were removed from hoophouses compared to zero plants in field plots, but plant loss may be confounded because priority was taken to remove pest-infested watermelon plants from hoophouses.

Approximately 60% more Cherokee Purple plants were removed from field plots than hoophouses. More plants of Cherokee Purple were pulled than any other tomato variety. Brandywine, Mewaldt Cherry, and Mewaldt Roma plants also were removed more from field plots than hoophouses. Cour di Bue had 100% survival in both the field plots and hoophouses. Because plants were pulled late in the growing season, plant loss did not generate varying results in best case data for total, weekly, and cumulative yield compared to the original data set (results not shown). Of the plants pulled, all but one plant produced some harvestable yield during the growing season, even if only minimal. The reason for plant tomato loss was unknown, but the plant diagnostic report recommended reducing direct exposure to sunlight during overly hot days as corrective treatment.

Fruit damage from small rodents accounted for most of the waste for both tomato and watermelon yield. Total waste accounted for approximately 10% of total tomato and 25% of total watermelon yield in the hoop house and approximately 20% of total tomato and 40% of total watermelon yield in the field plots (results not shown).

Winter 2015-2016 Experiment

During the winter experiment, total yield over all varieties and over all successive plantings was significantly (K-W ANOVA, 1 d.f., $P = 0.014$) less in the field plots (mean ± SE; 31 g ± 12) than in hoophouses (130 g ± 10). Only arugula and spinach were harvested from the field plots from successive planting 1 on harvest dates of 4 Mar and 18 Apr 2016. Other successive plantings of arugula and spinach as well as all successive plantings of other crops died off due to frost heave of the soil surface. Because field plot yields were typically zero, all further data analyses only considered plants grown in hoophouses.

When arugula was analyzed individually over all harvest dates, total, weekly, and cumulative yield significantly differed among the four successive plantings. Total yield in successive planting 1 was significantly greater than all other successive plantings (Table 3.5A).

Total yield of successive planting 4 of arugula was significantly less than all other successive plantings, whereas the two intermediate successive plantings (2 and 3) were not significantly different from one another. Weekly and cumulative yield of arugula was significantly greater in successive planting 1 than all other successive plantings (Table 3.5A). Weekly and cumulative yield in successive plantings 2 and 3 did not significantly differ, and successive planting 4 was significantly less than all other successive plantings.

Total, weekly, and cumulative yield significantly differed among the four successive plantings when spinach was analyzed individually over all harvest dates. Spinach total, weekly, and cumulative yield was significantly greater in successive planting 1 than in successive plantings 2, 3, and 4 (Table 3.5B). Weekly and cumulative yield in successive planting 2 and 3 did not significantly differ, and weekly yield of successive planting 3 and 4 did not differ. Cumulative yield of successive planting 4 was significantly less than all other successive plantings (Table 3.5B).

Total, weekly, and cumulative yield for leafy green crops was significantly different among varieties when the data was subset to a single successive planting and over all harvest dates. For successive planting 1, total yield did not significantly differ among varieties (Table 3.6). In contrast, spinach plants produced significantly more than arugula in successive plantings 2 and 4 by approximately 30% and 700%, respectively. Total yield was not significantly different between arugula and spinach plants in successive planting 3 (Table 3.6). Weekly yield of kale in successive planting 1 was significantly less than weekly yield of arugula and spinach when planting area was considered by approximately 120% and 80%, respectively. However, cumulative yield in successive planting 1 was greater for arugula plants than either of the two other crops, and spinach cumulative yield was significantly greater than kale (Table 3.6). Weekly and cumulative yield of arugula and spinach plants was not significantly different in successive planting 2. For the final two successive plantings 3 and 4, spinach weekly yield was significantly

greater than arugula weekly yield. However, cumulative yield did not differ between crops in successive planting 3. Spinach in successive planting 4 produced a greater cumulative yield than arugula (Table 3.6).

Total yield among successive plantings was significantly different when data was further subset by each variety on each harvest date (Fig. 3.6). For arugula plants, successive planting 1 had a significantly greater weekly yield than all other successive plantings over all harvest dates except 22 Feb 2016, in which successive planting 2 was not significantly different than 1 (Fig. 3.6A). Arugula plants were harvested in all hoophouse raised bed on 4 Mar 2016 due to bolting. Cumulative yield was always significantly greater for arugula in successive planting 1 than all other successive plantings (Fig. 3.6B). On 22 Feb 2016, arugula cumulative yield of successive planting 2 was significantly greater than both successive planting 3 and 4. Weekly yield of spinach plants was significantly greater in successive planting 1 than all other successive plantings until harvest on 4 Mar 2016; after that date, successive planting 1 and 2 were no longer significantly different (Fig. 3.6C). Spinach cumulative yield on all harvest dates was significantly greater in successive planting 1 than all other successive plantings (Fig. 3.6D). Cumulative yield of successive plantings 2, 3, and 4 were not significant on the first harvest date or the final two harvest dates.

Total yield of single harvest crops (three root crops and two leafy greens) varied significantly between the two harvest dates of 4 Mar and 18 Apr 2016 that were used in order to clear raised beds for the incoming summer crops. The later harvest date had a significantly (K-W ANOVA, 1 d.f., $P < 0.001$) greater total yield (341 ± 44) comparing all varieties and successive plantings than the earlier harvest (35 ± 81). Harvest was minimal on 4 Mar; therefore all further analyses only considered plants harvested on 18 Apr.

Total yield of successive plantings were significantly different within a respective crop. Beet root, Sugarsnax, and beet greens all had significantly greater total yield from successive

planting 1 than all other three successive plantings (Table 3.7); the difference between successive planting 1 and 2 for those crops was over 300%. For beet root and beet green crops, total yield from successive planting 2 was significantly greater than yield from the remaining successive plantings, whereas Sugarsnax total yield from successive planting 2 was only significantly greater than the successive planting 4. The first three successive plantings of Mokum and Claytonia did not produce significantly different total yield within each variety, but yield of the final successive planting was significantly less than yield in all preceding successive plantings (Table 3.7).

Total yield was significantly different among crop types within each of the four successive plantings (Table 3.8). The single harvest crops were subset further into root crops and greens for analysis of differences between similar crop type. Of the root crops, total yield of Sugarsnax in successive planting 1 was significantly greater than Mokum by approximately 170% but was not significantly different from beet root total yield (Table 3.8). Total yield among varieties was not significant in successive planting 2. Sugarsnax total yield in successive plantings 3 and 4 were significantly greater than both of the other root crops. Total yield of single harvest greens did not significantly differ between the two varieties.

Days to first harvest (DTH), which is measured from the date seeds were sown to the first harvest date, differed among successive plantings. Successive planting 1 of arugula and spinach were first harvested on December 1, which took 61 DTH. Both varieties were harvested after 81 days for successive planting 2. However, successive planting 3 differed between the two crops. Arugula took 112 DTH, in contrast to spinach, which only took 82 DTH. Successive planting 4 of arugula is confounded by the first harvest date also being the final harvest date, when bolting occurred. Spinach was harvested at 90 days for successive planting 4.

Damage to crops was minimal during the winter experiment, and the best case scenario data, which removed plant yield on a particular date due to pest damage, did not generate

significantly different results in total, weekly, and cumulative plant yield for either repeat or single harvest plants (results not shown).

LDMC data were subset to each individual winter crop, over all harvest dates, and LDMC of successive plantings did not significantly differ within any crop (results not shown). LDMC was significantly different among leafy green crops when data was subset by leafy greens and root crops, over all successive plantings and harvest dates (Table 3.9A). Kale LDMC was significantly greater than arugula, beet greens and Claytonia. In addition, arugula, beet greens, and spinach were significantly greater than Claytonia. No significant differences in LDMC among root crops occurred (Table 3.9B).

Summer 2016 Experiment

A major objective of the Summer 2016 experiment was to investigate if time of planting affected yield of watermelons and tomatoes between field plots and hoophouses. The early planting treatment resulted in zero plant survival in the field plots in contrast to only minor frost damage to plant growth tips in the hoophouses. Damage to hoophouse plants was not detrimental to plant survival. Although we replanted field plots within a week of initial planting for the early planting treatment, field plot plants did not survive in the early planting treatment, which resulted in zero yield from the early planting treatment in the field plots. For the late planting treatment, plants survival in the field plots was near 100%. However, the growing season for field plots was not long enough for marketable fruit production, and thus yield for the late planting treatment was also zero in field plots within the studied growing season. All further analyses only considered hoophouse grown plants.

Data was first analyzed for significant planting treatment effects. Total yield was significantly greater (K-W ANOVA, 1 d.f., $P = 0.0033$) over all harvest dates and plant varieties in the early planting treatment (6.38 kg ± 0.95) than the late planting treatment (2.19 kg ± 0.79).

For analyses of further subsets of data over both varieties and all harvest dates, watermelon total yield was not significant between planting treatments (Table 3.10A). When each watermelon variety was analyzed individually, neither variety had significantly greater total and weekly yield in either planting treatment (Table 3.10B). However, both Blacktail Mountain and Sugar Baby had significantly greater cumulative yield in the early planting treatment than the late planting treatment by 185% and 45%, respectively.

Consistent weekly harvest of watermelon fruit was not feasible due to time constraints, therefore it is not sensible to look at weekly and cumulative yield across harvest dates. However, the first harvest date for the early planting treatment was 10 Jul 2016 for Sugar Baby. The first harvest date for Sugar Baby plants in the late planting treatment was 24 Jul 2016. Weekly and cumulative yield was not significant between planting treatments for the remainder of the growing season. Blacktail Mountain watermelons were harvested on similar dates as Sugar Baby, although cumulative yield of Blacktail Mountain in the early planting treatment was greater than the late planting treatment on 14 Aug. But similar to Sugar Baby, weekly and cumulative yields were not significantly different between early and late planting treatments for any previous or succeeding harvest dates. Additionally in the early planting treatment, both watermelon varieties took 92 days to first harvest, calculated from the planting treatment date to the first harvest, in contrast to only 44 days in the late planting treatment.

Nonmarketable watermelon fruit only occurred on plants from the early planting treatment. Dates of harvested waste ranged from 19 Jun 2016 to 17 Jul 2016 as a result of stems breaking from trellised vines. Total waste of Blacktail Mountain and Sugar Baby varieties was 0.184 and 0.357 kg, respectively. Note that fruit was not fully developed at the time of weighing.

Over all varieties and all harvest dates, tomato total yield was significantly greater for plants grown in the early planting treatment than the late planting treatment by approximately 19 times (Table 3.11A). When each tomato variety was analyzed individually, not all varieties were

significantly affected by planting treatment. Total yield for Black Cherry did not significantly differ between the early and late planting treatment (Table 3.11B). However, total yield was significantly greater for New Yorker and Pink Berkeley Tie Dye varieties in the early planting compared to total yield of plants of the late planting by approximately 20 times. Weekly and cumulative yield of the early planting treatment were significantly greater for all varieties, over all harvest dates, compared to yield of plants in the late planting treatment.

Differences in total, weekly, and cumulative yield occurred among tomato plant varieties within a planting treatment (Table 3.12). Total yield of New Yorker in the early planting treatment was significant and approximately 300% greater than Black Cherry (Table 3.12). Total yield of New Yorker in the late planting treatment was significantly greater by approximately 10% and 100% than Black Cherry and Pink Berkeley Tie Dye, respectively. Weekly yield of New Yorker and Pink Berkeley Tie Dye plants in the early planting treatment, were both significant and approximately 300% and 260% greater than Black Cherry weekly yield, respectively (Table 3.12). Cumulative yield was similarly different among varieties in the early planting treatment, in which New Yorker and Pink Berkeley Tie Dye were significantly greater by approximately 180% and 260% than Black Cherry cumulative yield, respectively. Because harvests for the late planting treatment did not begin until three weeks before the final harvest, weekly and cumulative yield do not relay reliable information for those varieties, and thus are not reported.

Days to first harvest (DTH) was different among varieties and between the two planting treatments. In the early planting treatment, Black Cherry and New Yorker varieties took 85 DTH and were harvested on 3 Jul. Pink Berkeley Tie Dye plants from the early planting treatment took only 70 DTH and were initially harvested on 19 Jun. In the late planting treatment, DTH of all three varieties was 65 days and harvest did not occur until 14 Aug. Note that for both planting treatments, seed sowing dates for tomato plants were two weeks prior to transplanting into plots.

Plant loss impacted some varieties more than others, and planting treatment was also a factor in percent plant loss. Plants were removed throughout the growing season as necessary. Plant loss was caused by aphid damage and by both Fusarium and Verticillium wilts in both watermelon and tomato plants, although only tomato plant loss was recorded thoroughly within hoophouses. The first plants were pulled from the early planting treatment on 6 Jul, which was almost four months after planting (Figure 3.7). Plants from the late planting treatment were initially pulled on 26 Jul, which was just over a month after planting. The number of plants pulled within a variety was always greater in the early planting treatment than the later treatment, but plants from the late planting treatment had a more rapid response to the wilts compared to the early treatment. Black Cherry plant removal was greater than either of the other varieties, with over 50% removed from the early planting treatment by 26 Jul. New Yorker had the least number of plants pulled in both the early and late planting treatment, with only 20% and 0% pulled respectively.

Utilizing plant removal information, a best case scenario of the original summer 2016 data set was generated and analyzed to develop a potentially more representative idea of plant yield without loss due to disease and pest damage. Accounting for plant loss, total harvestable yield in the early planting treatment increased by 65% in Black Cherry plants, approximately 20% in New Yorker, and 45% in Pink Berkeley Tie Dye plants (Figure 3.8). Differences in the original data set and best case scenario was most prominent when comparing varietal differences in weekly and cumulative yield within the early planting treatment. Pink Berkeley Tie Dye weekly and cumulative yield was significantly greater than Black Cherry yield by 76% and 70%, respectively. Pink Berkeley Tie Dye cumulative yield was also significantly greater than New Yorker cumulative yield by over 30%. In addition, Black Cherry total yield was significantly greater in the early planting treatment than the late planting treatment in the best case dataset, whereas in the original dataset, the two planting treatments did not differ. Early planting

treatment yield was still significantly greater in all varieties than the late planting treatment; and within the late planting treatment, variety differences also did not change (results not shown).

DISCUSSION

Summer 2015 Experiment

Mulch treatments had no significant effect on tomato yield for plants grown in both the hoophouses and field plots. In contrast to previous literature, plastic mulch did not cause tomato yield to significantly increase compared to untreated plants (Hana et al., 1997). However, we note that mulch treatments in our experiments were applied to the raised beds in mid-July, at which time tomato plants had already begun to set fruit and symptoms of plant decline were already developing. However, white on black plastic mulch increased cumulative yield of watermelons grown in field plots, similar to results in other studies (Soltani et al., 1995). Additionally, cumulative yield of watermelons were positively affected by compost mulch in both the hoophouses and field plots compared to no mulch treatment, and wood mulch benefited hoophouse grown watermelons. The addition of compost increases yield and reduced incidence of disease to a greater extent in hoophouses than field grown plants (Baysal et al., 2009). During the summer 2015 experiment, all raised beds received compost before planting. With the addition of compost as a mulch treatment, cumulative yield increased in hoophouse and field plot watermelon plants, although disease incidence was unchanged.

Total yield of watermelon and tomato plants grown in the hoophouses was greater than field plot grown plants. However, days to harvest was not different between plot types for either plant type. The overall greater total yield in the hoophouses indicates an underlying hoophouse effect. The average minimum temperature in the Reno, Nevada area during July and August is approximately 14 °C, and by September minimum temperatures have dropped to 9 °C. Tomatoes that experience temperatures between 10-15 °C and above 35 °C can experience physiological and environmental disorders, such as irregular fruit or cause flowers to fall off (Hunter et al.,

2010). Watermelon plants require slightly warmer minimum temperatures for growth and fruit development with an optimal range between 20-26 °C day and 18-21 °C night temperatures (Jett, 2006). Hoophouses maintain a higher optimal temperature for warm season crops by reducing minimum temperatures and increasing average soil temperature (Dorais et al., 2001; Millner et al., 2009; Wittwer and Castilla, 1995). During the summer 2015 experiment, watermelon total yield was greater for plants grown in the hoophouses versus field plots over both varieties. Hoophouse grown watermelons had two peak weekly yields on 14 Aug and 4 Sept for both varieties individually. In contrast, field plots had peak yield during the 4 Sept harvest date only. Earlier yield in the hoophouses indicates watermelons benefit near the beginning of the growing season from hoophouse growth. The initial harvest in the hoophouses could have been a result of potential warmer temperatures in the hoophouses during flowering and fruit set. The difference in total yield between hoophouse and field grown melons during more mild, warmer growing seasons was much smaller than that during cooler growing seasons, during which hoophouses performed markedly better (Waterer, 2003).

Peak weekly yield was always greater in hoophouse grown tomato plants than field plots during the summer 2015 experiment. However the date of peak yield differed between plot types. Peak yield in the hoophouses for Cour di Bue was on 11 Sept, whereas peak yield in the field plots was 28 Aug. Cour di Bue, weekly and cumulative yields at any given harvest date were typically greater throughout the growing season in hoophouses than field plots until the final harvest date. Therefore, Cour di Bue consistently grew better in the hoophouse environment. Cherokee Purple had a greater yield early on in the growing season, which resulted in an initial increase in yield in the hoophouses over field plots. However, field plot and hoophouse weekly yield did not differ much after the first two harvest dates. Brandywine weekly yield was initially greater in the field plots, but by the end of the growing season, hoophouse yield exceeded field plots, which resulted in total yield being greater in the hoophouses. Weekly yield for Mewaldt

Roma, a locally developed variety, was similar between hoophouses and field plots for the first part of the growing season, but hoophouses achieved greater yield near the end of the season such that hoophouse total yield was greater than field plots. Both Brandywine and Mewaldt Roma benefited greatest from hoophouse growing conditions later in the season. On the other hand, the other local variety, Mewaldt Cherry maintained a weekly yield in hoophouses similar to field plots until the very end of the growing season. Mewaldt Cherry only slightly benefited from hoophouses. Hoophouses provide protection from late season frost, although low temperatures in the fall tend to slow crop development (Waterer, 2003). Towards the end of production, hoophouse weekly yield of the two local varieties and Brandywine were increasing at a greater rate than field grown plants, indicating these varieties may benefit from late season extension in the hoophouses. Even though early season tomatoes yield a higher market value than later season tomatoes (Rogers and Wszelaki, 2012; Davison and Lattin, 2015), heirloom tomato varieties have a higher market value than hybrid fruit (Jordan, 2007). Days to harvest for hoophouses and field plots did not differ during the summer 2015 experiment. However, a planting date of mid-June provided greater benefit to hoophouse grown plants over field plots (Table 3.3), even though the difference was sometimes not always present in weekly yield at any particular harvest date.

Of the two local tomato varieties grown, Mewaldt Roma performed better in the hoophouses, which is similar to a study that also demonstrated a locally developed Roma variety grown in the hoophouses out performed field grown plants (Davison and Lattin, 2015). However, Mewaldt Roma was slow to begin producing fruit compared to other varieties regardless of plot type during the summer 2015 experiment. Similar to a previous study, Cherokee Purple, which is a commercially available heirloom variety, did not perform significantly better in hoophouses than field plots during a single season of growth (Davison and Lattin, 2015). However, heirloom varieties have demonstrated a higher level of marketability and average yield when grown under

hoophouse conditions versus field grown plants (Rogers and Wszelaki, 2012; Davison and Lattin, 2015).

Mammal pest pressure was greater in field plots than hoophouses. Watermelon and tomato fruit were both subject to squirrel damage. Protecting fruit from damage in the hoophouses was easier than field plots because of the style of hoophouses used at the MSFL, which had wood walls from ground level up to three feet, which in turn greatly reduced yield lost to rodents in the hoophouses. In addition, plant loss was more prevalent in the field plots than hoophouses for all tomato varieties. The cause of tomato decline was unknown, but symptoms included yellowing and curling of leaves, as well as purple veining, which eventually led to plant death. Symptoms were less prevalent in hoophouses than field grown tomato plants during the summer 2015 experiment, which is in agreement to previous literature (Rogers and Wszelaki, 2012). During a study in western Nevada, yield in hoophouses was greater than field grown tomatoes even under high disease pressure from beet curly top virus (Davison and Lattin, 2015). In contrast, watermelon plant loss was due to an aphid infestation late in the season in both hoophouse and field plot plants. Plants were pulled from the hoophouses to prevent further infestation and spread.

Overall, heirloom watermelon and tomato plants benefited from hoophouses in terms of total yield, regulating environmental plant stressors, and the ability to manage pest problems. Additionally, compost as a mulch treatment tended to generate higher yield in hoophouse grown watermelon plants.

Winter 2015 – 2016 Experiment

The earliest successive planting had a higher total, weekly, and cumulative yield than all other successive plantings for both varieties of leafy greens harvested repeated times throughout the growing season. Greater yield overall indicates these differences were consistent over all harvest dates, which is comparable to individual harvest dates throughout the growing season

(Figure 3.6). The initial four harvest dates for arugula successive planting 1 were all significantly greater than the other successive plantings. Regardless of successive planting, the final harvest date was on 4 Mar because of bolting, which explains the substantial weekly yield on that date. Both intermediate successive plantings were generally unproductive until the final harvest. In addition, successive planting 4 did not produce much total yield on the final harvest date. Low yield suggests planting arugula much after early October in the high desert may not provide substantial growth over winter to generate substantial yield before spring temperatures get above 26 °C in the hoophouse and bolting occurs (WSU extension, Morales et al., 2006).

Spinach initial harvest date of successive planting 1 had a higher weekly yield than all other successive plantings, indicating the earlier planting date generated a substantial head start in yield. Maximum growth rate for spinach occurs between 15-24 °C, whereas growth ceases at or below 2 °C (Ernst et al., 2012). Towards the end of the season on 17 Mar, all four successive plantings began producing a steady increase in weekly yield through the final harvest date of 18 Apr, which suggests that growing conditions within the hoophouses were reaching something close to optimal for spinach crops. The later three successive plantings were similar in weekly yield for most of winter until growth resumed on 17 Mar. These results suggest that a planting date of 2 Oct will generate enough growth before temperatures cool inside the hoophouse to produce fairly consistent weekly yield throughout winter and generate a substantial head start on spring harvest. In addition, the later planting dates produced fairly small amounts of weekly yield until temperatures warmed in early spring (Knewtson, 2008), which resulted in total yield greater for successive planting 1, indicating the earliest planting date generated the greatest benefit.

Days to first harvest of successive planting 1 (sown on 2 Oct) was 20 days less than successive planting 2 (23 Oct) for both arugula and spinach. Successive planting 3 (13 Nov) of arugula took an additional 30 days to harvest, whereas spinach was the same as successive planting 2. Finally, successive planting 4 (4 Dec) for spinach was 90 days to first harvest,

whereas arugula was confounded by plants pulled because of bolting. The shorter days to harvest of earlier successive plantings suggests that plants had more rapid growth than later successive plantings. The similarity in DTH of spinach successive planting 2 and 3 suggests that similar growing conditions are present for spinach in late October and early November. However, sowing successive planting 1 three weeks earlier than successive planting 2 resulted in six weeks of additional harvest for both, and successive planting 1 had an additional 12 weeks of harvest compared to successive planting 3. Because yield of successive planting 1 was much greater for both arugula and spinach crops, both crops should be planted in early October for adequate plant development and continued harvest during the winter months.

Total yield of repeat harvest leafy greens in successive planting 1 were not different, although weekly and cumulative yield of kale was significantly less than both arugula and spinach when planting area was taken into account. The initial harvest date for all three crops was on 1 Dec. However weekly yield was initially greatest in arugula, and spinach was second in weekly yield and kale produced the least through February. Weekly yield of kale on 4 Mar and on subsequent harvest dates was increasing until final harvest, which suggests that kale grew better later in the season. In contrast, both arugula and spinach had greater yield earlier in the growing season. Kale was beginning to bolt in the hoophouses in early April. Spinach was still generating healthy new growth through the final pull date on 18 Apr.

Although harvest date for single harvest crops was predetermined, days to harvest is informative because the successive plantings had different total yield, which may provide information on whether different yields were due to planting date or other influences in the hoophouses. Days to harvest was considerably long in all successive plantings compared to typical harvest times for all crops grown, suggesting days of growth was not the underlying cause of low yield. Carrots and beet root grow best in temperatures between 15-18 °C, and Claytonia 15-25 °C. All crops grown were cool season crops, and for optimal growth, slightly warmer

temperatures were required than present in Reno, NV during winter. During October and November, average day temperatures were 21 and 13 °C and night temperatures were 4 and 0 °C, respectively. However in December and January, 7 °C day and -4 °C night temperatures are the average. The warmer temperature needs of these crops may explain why the later successive plantings did not perform as well as the earliest successive plantings, even though hoophouses provide warmer day time temperatures when the sun is out (Wien, 2009). As indicated by a minimal harvest of all crops on 4 Mar, growth up to that date was insufficient for harvest and not of marketable size. However on the final harvest date, most successive harvests produced some yield, suggesting considerable growth occurred from mid-March and early-April. Therefore, the long days to harvest did not generate considerably greater yields, but instead crops remained stagnant until spring when growth resumed.

Of the root crops, Sugarsnax had higher yield over all successive plantings than either of the other root crops, and beet greens and claytonia were not significantly different from one another. However, beet roots and greens can be marketed together as a single crop, or as an addition to salad mix and root crop separately. If sent to market separately, beets overall had a higher yield in the first successive planting than the other crops.

Pest damage was minimal during the winter season, but spider mites and aphids were present on spinach crops. Damage from rodents was mainly to kale and spinach. However, when analyzed as a best case scenario dataset, differences were not significant among varieties or successive plantings, suggesting the wire netting placed on the hoophouse sides prevented most squirrels from entering the hoophouses in winter. Another notable source of damage was root cracking in beet root successive planting 1 from infrequent watering, which caused irregular soil moisture and surface drying. The irrigation pattern was altered and water was subsequently applied for less time and more frequently, which produced root crops in successive planting 2 that were not cracked.

Leaf dry matter content (LDMC) is an indicator of leaf composition and leaf thickness, and a higher LDMC tends to correlate to leaves more capable of resisting environmental stressors (Wilson et al., 1999). Kale is a cold hardy vegetable with high LDMC as indicated by thick leaf tissue. In contrast, Claytonia has a high water content, which can explain the low LDMC (Wilson et al., 1999).

Overall, repeat harvest greens are a more successfully grown crop, when planted no later than early October that will generate yield throughout the winter months and generate a head start on spring harvest.

Summer 2016 Experiment

Hoophouses used to grow watermelons are advantageous, because vertical trellising of vines allows more plants per area than field grown plants (Jett, 2006). However, plants were grown horizontally across the ground after initial trellising during the summer 2016 experiment because fruit was breaking off the stem from the weight. In the previous summer 2015 experiment, fruit was given support, but due to time constraints, it was not feasible to sling each fruit in 2016. Adequate fruit support is an important consideration for watermelons grown in hoophouses. Due to fruit loss in early June, the first harvest may have been delayed in the early planting treatment. Locally grown watermelons are typically harvested in August and September for market (Lattin Farms, Fallon, NV).

During the summer 2016 experiment, both watermelon varieties at both planting treatments were harvested in the hoophouses by mid-July, gaining at least two weeks on the local market scene. However, days to first harvest (DTH) of the second planting treatment was nearly half the DTH for the early planting treatment. The shorter DTH for the late planting treatment suggests that plants had more rapid growth that at least partially offset the advantage of a greater growing period that plants started in the early planting treatment had. However, the initial harvest date for the early planting treatment was two weeks prior to the first harvest date of late planting

treatment watermelons. In addition, cumulative yield was significantly greater in the hoophouses than field plots for both varieties, which suggests the earlier planting date allowed plants to start yielding fruit earlier than the late planting treatment. Watermelon varieties did not perform differently within or between planting treatments.

Optimal temperature for watermelon growth and development is considerably higher than the average day and night temperature range for the high desert during June and July. However, hoophouses may provide the necessary optimal temperature range by increasing temperatures during the transition seasons by almost 10-15 °C in sunny climates compared to outside (Wien, 2009) and maintain temperatures 5-8 °C warmer than field plots in spring (Roger and Wszelaki 2012). Row covers can also provide up to 2-6 °C of additional warmth (Wells and Loy, 1993; Ward and Bomford, 2013). For future studies, warming the soil prior to transplanting with dark plastic mulch may also increase watermelon growth and early fruit development to aid in season extension (Jett, 2006).

By July during the summer 2016 experiment, watermelon plant growth in the early planting treatment slowed considerably and the late plant treatment caught up and surpassed the early planting treatment. Plant loss due to fusarium and verticillum wilts was substantial in the early planting treatment (personal observation). However, a final harvest date on 18 Sept produced 100% waste for both watermelon varieties at both planting dates (results not shown). Watermelon centers were liquid and stringy.

The use of row cover within a hoophouse provided close to 100% survival of tomato plants planted in March and resulted in an initial harvest date of early July during the summer 2016 experiment, which are similar results to another experiment located in the high desert of Utah (Hunter et al., 2012). In contrast to previous literature on field grown plants (Ankara, 2001; Waggoner, 1958), row covers were unable to provide frost and wind protection for early field planted tomatoes and watermelons during the summer 2016 experiment. High winds immediately

after planting the early treatment caused the row cover to blow off field plot plants and either directly caused damage by snapping stems or indirectly by allowing cold temperatures to damage plants. Seasonal variability clearly will impact the success of early planting dates in field plots. Hoophouses are beneficial for early season extension of tomato plants, which generated an earlier harvest date compared to field grown plants (Hunter et al., 2012; Roger and Wszelaki, 2012).

During the summer 2016 experiment, days to first harvest (DTH) was substantially longer for Black Cherry and New Yorker varieties in the early planting treatment than the late planting treatment. However, Pink Berkeley Tie Dye DTH was only five days longer for the early planting treatment than the late treatment, indicating growth was not greatly reduced during the cooler early season temperatures. New Yorker and Pink Berkeley Tie Dye had significantly greater total, weekly, and cumulative yields during the early planting treatment than the late planting treatment, indicating differences were consistent over time. However, only weekly and cumulative yield of Black Cherry were significantly greater in the early planting treatment. Harvest for all varieties in the late planting treatment did not begin until three weeks prior to the final harvest for the season, which gave the early planting treatment 6-8 weeks of additional yield. Peak weekly yield for all tomato varieties in the early planting treatment was on 14 Aug. Among varieties within the early planting treatment, Pink Berkeley Tie Dye began producing significantly greater weekly yield in the first part of the season, whereas both Black Cherry and New Yorker were slower to begin producing. New Yorker achieved greater weekly yield near the end of the growing season, surpassing Pink Berkeley Tie Dye in the final three harvests. Black Cherry began producing greater yield towards the end of the growing season, but compared to the other varieties, Black Cherry did not produce as well.

Accounting for plant loss in the best case scenario dataset, Pink Berkeley Tie Dye total yield was greater than Black Cherry, whereas in the original dataset that only included marketable fruit, the difference was not significant. New Yorker variety substantially increased in weekly

yield compared to Pink Berkeley Tie Dye in the later part of the growing season, but this increase in yield corresponds to a decrease in plant number in Pink Berkeley Tie Dye not accounted for in the original dataset. In the best case dataset, Pink Berkeley Tie Dye had a greater cumulative yield than New Yorker, but weekly and total yield between the two varieties remained unchanged. Black Cherry had the highest number of individual plants lost during the growing season for both planting treatments, which may explain the lower overall yield of Black Cherry compared to the other two varieties in the original dataset. In the best case scenario data, which accounted for plant loss, Black Cherry total yield was significantly greater in the early planting treatment than the late planting treatment, whereas the original data was not different.

The increased demand for locally grown, organic heirloom tomatoes and success of early season extension in the high desert may result in a product that is competitive in local markets with produce shipped from traditional market sources such as California.

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TABLES

Table 3.1. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2015 experiments that compare four different mulch treatments applied in both hoophouse and field study plots and for tomato and watermelon varieties. Least square means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different.

3.1A. Complete dataset (i.e. over all four hoophouses and both field plots and over all five tomato and both watermelon varieties, over all harvest dates). n = 42.

	K-W ANOVA		Mean ± standard error			
Yield	**d.f.**	**p value**	**None**	**Plastic**	**Compost**	**Wood**
Total yield (kg)	3	0.606	1.72 ± 0.22	1.92 ± 0.22	2.23 ± 0.27	2.03 ± 0.26
Weekly yield (kg)	3	0.978	0.28 ± 0.03	0.28 ± 0.04	0.32 ± 0.04	0.29 ± 0.00
Cumulative yield (kg)	3	0.598	0.95 ± 0.07	1.04 ± 0.07	1.13 ± 0.09	1.03 ± 0.08

3.1B. Data divided in hoophouse (HH) and field plot (FP) subsets, with each subset including data over all five tomato and both watermelon varieties, over all harvest dates. HH n = 28; FP n = 14.

		K-W ANOVA		Mean ± standard error			
Yield	**Plot**	**d.f.**	**p value**	**None**	**Plastic**	**Compost**	**Wood**
Total yield (kg)	HH	3	0.959	2.08 ± 0.28	2.28 ± 0.27	2.48 ± 0.35	2.34 ± 0.37
	FP	3	0.192	1.01 ± 0.31	1.20 ± 0.31	1,74 ± 0.41	1.39 ± 0.19
Weekly yield (kg)	HH	3	0.792	3.48 ± 0.04	3.27 ± 0.05	3.57 ± 0.05	3.36 ± 0.05
	FP	3	0.282	1.45 ± 0.04	1.83 ± 0.05	2.48 ± 0.05	1.98 ± 0.04
Cumulative yield (kg)	HH	3	0.987	1.18 ± 0.09	1.17 ± 0.10	1.24 ± 0.11	1.22 ± 0.11
	FP	3	0.068	5.03 ± 0.08	7.76 ±0. 11	9.12 ± 0.12	6.38 ± 0.07

3.1C. Data divided into subsets by type of plot (hoophouse (HH) or field plot (FP)) and by type of produce (over all five tomato varieties (Tom) or over both watermelon varieties (Melon)), over all harvest dates. HH Tom n = 20; HH Melon n = 8; FP Tom n = 10; FP Melon n = 4.

			K-W ANOVA		Mean ± standard error			
Yield	**Plot**	**Produce**	**d.f.**	**p value**	**None**	**Plastic**	**Compost**	**Wood**
Total yield	HH	Tom	3	0.435	2.01 ± 0.29	2.08 ± 0.26	1.64 ± 0.15	1.55 ± 0.19
(kg)		Melon	3	0.104	2.25 ± 0.67	2.77 ± 0.67	4.59 ± 0.77	4.32 ± 0.88
	FP	Tom	3	0.083	0.78 ± 0.21	1.00 ± 0.18	1.30 ± 0.25	1.31 ± 0.14
		Melon	3	0.764	1.60 ± 1.01	1.70 ± 1.03	2.84 ± 1.25	1.60 ± 0.61
Weekly yield	HH	Tom	3	0.253	0.33 ± 0.04	0.30 ± 0.04	0.24 ± 0.03	0.22 ± 0.02
(kg)		Melon	3	0.473	0.39 ± 0.10	0.40 ± 0.13	0.66 ± 0.15	0.62 ± 0.15
	FP	Tom	3	0.167	0.11 ± 0.02	0.14 ± 0.03	0.19 ± 0.04	0.19 ± 0.03
		Melon	3	0.465	0.23 ± 0.13	0.28 ± 0.15	0.41 ± 0.15	0.23 ± 0.13
Cumulative yield	HH	Tom	3	0.111	1.09 ± 0.10	0.96 ± 0.09	0.77 ± 0.06	0.73 ± 0.07
(kg)		Melon	3	**0.033**	1.40^{b} ± 0.21	1.68^{ab} ± 0.24	2.40^{a} ± 0.31	2.50^{a} ± 0.30
	FP	Tom	3	0.261	0.43 ± 0.06	0.51 ± 0.06	0.70 ± 0.10	0.62 ± 0.07
		Melon	3	**0.049**	0.68^{c} ± 0.24	1.43^{ab} ± 0.33	1.44^{a} ± 0.33	0.69^{bc} ± 0.18

Table 3.2. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2015 experiments that compare hoophouse and field study plots of two watermelon varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$

3.2A. Data divided by hoophouse (HH) and field plot (FP) subsets, over both watermelon varieties and all harvest dates. HH n = 32; FP n = 16.

	K-W ANOVA		Mean ± standard error	
Yield	**d.f.**	**p value**	**HH**	**FP**
Total yield (kg)	1	**0.039**	3.48 ± 0.40	1.93 ± 0.47

3.2B. Data divided into subsets by type of plot, hoophouse (HH) and field plot (FP), and further divided by Golden Midget (GM) and Sugar Baby (SB) watermelon varieties (Var) over all harvest dates. Per Variety, HH n = 16; FP n = 8.

		K-W ANOVA		Mean ± standard error	
Yield	**Var**	**d.f.**	**p value**	**HH**	**FP**
Total yield (kg)	GM	1	0.180	3.59 ± 0.66	2.17 ± 0.68
	SB	1	0.069	3.38 ± 0.48	1.70 ± 0.68
Weekly yield (kg)	GM	1	0.220	0.545 ± 1.07	0.31 ± 0.75
	SB	1	0.140	0.483 ± 0.97	0.26 ± 0.75
Cumulative yield (kg)	GM	1	**0.011**	2.19 ± 2.12	1.25 ± 1.48
	SB	1	**<0.001**	1.79 ± 1.97	0.87 ± 1.54

Table 3.3. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2015 experiments that compare hoophouse and field study plots of five tomato varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$.

3.3A. Data divided in hoophouse (HH) and field plot (FP) subsets, over all five tomato varieties and all harvest dates. HH n = 80; FP n = 40.

	K-W ANOVA		Mean ± standard error	
Yield	**d.f.**	**p value**	**HH**	**FP**
Total yield (kg)	1	**<0.001**	1.82 ± 0.12	1.10 ± 0.10

3.3B. Data divided into hoophouse (HH) and field plot (FP) subsets, and further divided into variety (Var) of Brandywine (BW), Cour di Bue (CdB), Cherokee Purple (CP), Mewaldt Cherry (MC), and Mewaldt Roma (MR) over all harvest dates. Per variety, HH n = 16; FP n = 8.

		K-W ANOVA		Mean ± standard error	
Yield	**Var**	**d.f.**	**p value**	**HH**	**FP**
Total yield (kg)	BW	1	**0.024**	2.20 ± 0.39	0.97 ± 0.17
	CdB	1	0.051	2.43 ± 0.27	1.63 ± 0.31
	CP	1	0.069	1.63 ± 0.21	1.00 ± 0.22
	MC	1	0.051	1.67 ± 0.11	1.29 ± 0.13
	MR	1	**0.008**	1.17 ± 0.12	0.59 ± 0.11
Weekly yield (kg)	BW	1	0.067	0.32 ± 0.06	0.14 ± 0.04
	CdB	1	**0.031**	0.41 ± 0.04	0.23 ± 0.05
	CP	1	0.180	0.23 ± 0.04	0.14 ± 0.03
	MC	1	0.086	0.24 ± 0.02	0.18 ± 0.02
	MR	1	**0.005**	0.17 ± 0.02	0.08 ± 0.02
Cumulative yield (kg)	BW	1	0.580	0.74 ± 0.11	0.45 ± 0.06
	CdB	1	**0.003**	1.44 ± 0.12	0.87 ± 0.12
	CP	1	**0.001**	0.98 ± 0.08	0.54 ± 0.08
	MC	1	0.260	0.80 ± 0.06	0.67 ± 0.07
	MR	1	**0.047**	0.48 ± 0.05	0.29 ± 0.04

Table 3.4. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2015 experiments that compare five tomato varieties, Brandywine (BW), Cour di Bue (CdB), Cherokee Purple (CP), Mewaldt Cherry (MC), and Mewaldt Roma (MR), within hoophouse and field study plots. Means and standard errors are shown for total yield (total amount of marketable produce harvested over all harvest dates). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. HH, n = 16; FP, n = 8.

		K-W ANOVA		Mean ± standard error				
Yield	**Plot**	**d.f.**	**p value**	**BW**	**CdB**	**CP**	**MC**	**MR**
Total yield	HH	4	**0.002**	$2.20^{ab} \pm 0.39$	$2.43^{a} \pm 0.27$	$1.63^{bc} \pm 0.21$	$1.67^{bc} \pm 0.11$	$1.17^{c} \pm 0.12$
(kg)	FP	4	**0.019**	$0.97^{ab} \pm 0.17$	$1.63^{a} \pm 0.31$	$1.00^{ab} \pm 0.22$	$1.29^{a} \pm 0.13$	$0.59^{b} \pm 0.11$

Table 3.5. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Winter 2015-2016 experiments that compare four different successive plantings, sown beginning on Oct 2 and every three weeks until Dec 4, applied in the hoophouses for repeat harvest leafy greens, arugula and spinach varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. Per successive planting, n = 8.

3.5A. Data subset to arugula variety over all harvest dates.

	K-W ANOVA		Mean ± standard error			
Yield	**d.f.**	**p value**	**1**	**2**	**3**	**4**
Total yield (g)	3	**<0.001**	$1663^{a} \pm 247$	$323^{b} \pm 76$	$249^{b} \pm 75$	$12^{c} \pm 12$
Weekly yield (g)	3	**<0.001**	$226^{a} \pm 33$	$42^{b} \pm 12$	$25^{bc} \pm 8$	$4^{c} \pm 2$
Cumulative yield (g)	3	**<0.001**	$826^{a} \pm 74$	$121^{b} \pm 19$	$87^{b} \pm 16$	$7^{c} \pm 3$

3.5B. Data subset to spinach variety over all harvest dates.

	K-W ANOVA		Mean ± standard error			
Yield	**d.f.**	**p value**	**1**	**2**	**3**	**4**
Total yield (g)	3	**0.010**	$1681^{a} \pm 358$	$651^{b} \pm 101$	$425^{b} \pm 62$	$474^{b} \pm 101$
Weekly yield (g)	3	**<0.001**	$182^{a} \pm 25$	$57^{b} \pm 11$	$40^{bc} \pm 8$	$35^{c} \pm 9$
Cumulative yield (g)	3	**<0.001**	$477^{a} \pm 58$	$107^{b} \pm 21$	$61^{c} \pm 13$	$66^{c} \pm 16$

Table 3.6. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Winter 2015-2016 experiments that compare three different varieties in successive planting (Succ) 1 and two varieties in the remaining three successive plantings applied in the hoophouses for repeat harvest leafy greens, arugula, kale, and spinach varieties. Successive planting 1 was sown on Oct 2, the remaining successive plantings were sown every three weeks until Dec 4. Kale means account for a larger planting area in successive planting 1 than the other two varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. n = 8.

		K-W ANOVA		Mean ± standard error		
Yield	**Succ**	**d.f.**	**p value**	**Arugula**	**Kale**	**Spinach**
Total yield (g)	1	2	0.101	1663 ±247[a]	1199[a] ± 285	1682[a] ± 358
	2	1	**0.027**	323 ± 76	-	651 ± 101
	3	1	0.074	249 ± 75	-	425 ± 62
	4	1	**<0.001**	12 ± 12	-	474 ± 101
Weekly yield (g)	1	2	**0.023**	226[a] ± 33	102[b] ± 23	182[a] ± 25
	2	1	0.062	42 ± 12	-	57 ± 11
	3	1	**0.025**	25 ± 8	-	40 ± 8
	4	1	**<0.001**	4 ± 2	-	35 ± 9
Cumulative yield (g)	1	2	**<0.001**	826[a] ± 74	177[c] ± 40	477[b] ± 58
	2	1	0.584	121 ± 19	-	107 ± 21
	3	1	0.196	87 ± 16	-	61 ± 13
	4	1	**<0.001**	7 ± 3	-	66 ± 16

Table 3.7. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Winter 2015-2016 experiments that compare four successive plantings, sown beginning on Oct 2 and every three weeks until Dec 4, within each single harvest variety. Means and standard errors are shown for total yield (total amount of marketable produce harvested over all harvest dates). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. n = 16.

		K-W ANOVA		Mean ± standard error			
Yield	**Var**	**d.f.**	**p value**	**1**	**2**	**3**	**4**
Total yield (g)	Beet root	3	**0.008**	$636^{a} \pm 141$	$130^{b} \pm 43$	$15^{c} \pm 15$	$0^{c} \pm 0$
	Mokum	3	**<0.001**	$534^{a} \pm 151$	$278^{a} \pm 76$	$167^{a} \pm 55$	$23^{b} \pm 14$
	Sugarsnax	3	**<0.001**	$1436^{a} \pm 340$	$340^{b} \pm 101$	$199^{bc} \pm 55$	$118^{c} \pm 46$
	Beet greens	3	**<0.001**	$1309^{a} \pm 277$	$288^{b} \pm 82$	$32^{c} \pm 15$	$13^{c} \pm 10$
	Claytonia	3	**0.001**	$803^{a} \pm 370$	$381^{a} \pm 130$	$116^{a} \pm 44$	$0^{b} \pm 0$

Table 3.8. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Winter 2015-2016 experiments that compare varietal differences of three root crops and two leafy green crops within each successive planting (Succ), sown beginning on Oct 2 and every three weeks until Dec 4. Means and standard errors are shown for total yield (total amount of marketable produce harvested over all harvest dates). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. n = 16.

		K-W ANOVA		Mean ± standard error		
Yield	**Succ**	**d.f.**	**p value**	**Beet root**	**Mokum**	**Sugarsnax**
Total yield (g)	1	2	0.106	$636^{a} \pm 141$	$534^{a} \pm 151$	$1436^{a} \pm 340$
	2	2	0.167	$130^{a} \pm 43$	$278^{a} \pm 76$	$340^{a} \pm 101$
	3	2	**0.005**	$15^{b} \pm 15$	$167^{b} \pm 55$	$199^{a} \pm 55$
	4	2	**0.008**	$0^{b} \pm 0$	$23^{b} \pm 14$	$118^{a} \pm 46$
				Beet greens	**Claytonia**	
	1	1	0.208	1309 ± 277	803 ± 370	
	2	1	0.674	288 ± 82	381 ± 130	
	3	1	0.131	32 ± 15	116 ± 44	
	4	1	0.144	13 ± 10	0 ± 0	

Table 3.9. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Winter 2015-2016 experiments that compare varietal differences of three root crops and two leafy green crops over all four successive plantings, sown beginning on Oct 2 and every three weeks until Dec 4. Means and standard errors are shown for leaf dry matter content (LDMC). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different.

3.9A. Data subset to leafy greens over all harvest dates.

	K-W ANOVA		Mean ± standard error				
Measure	**d.f.**	**p value**	**Arugula**	**Beet green**	**Claytonia**	**Kale**	**Spinach**
LDMC	4	**<0.001**	$0.12^{b} \pm 0.01$	$0.12^{b} \pm 0.01$	$0.11^{c} \pm 0.02$	$0.17^{a} \pm 0.02$	$0.13^{ab} \pm 0.01$

3.9B. Data subset to root crops over all harvest dates.

	K-W ANOVA		Mean ± standard error		
Measure	**d.f.**	**p value**	**Beet root**	**Mokum**	**Sugarsnax**
LDMC	2	0.349	$0.13^{a} \pm 0.01$	$0.12^{a} \pm 0.00$	$0.11^{a} \pm 0.00$

Table 3.10. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2016 experiments that compare two different planting dates applied in both hoophouse and field study plots and for both watermelon varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$.

3.10A. Data subset to watermelons, with each subset including data over both varieties and over all harvest dates. n = 8.

	K-W ANOVA		Mean ± standard error	
Yield	**d.f.**	**p value**	**3/11**	**6/11**
Total yield (kg)	1	0.260	22.22 ± 2.4	16.73 ± 3.8

3.10B. Data subset to each watermelon variety Blacktail Mountain (BTM) and Sugar Baby (SB), with each subset including all harvest dates. n = 4.

		K-W ANOVA		Mean ± standard error	
Yield	**Var**	**d.f.**	**p value**	**3/11**	**6/11**
Total yield (kg)	BTM	1	0.600	21.5 ± 4.9	15.7 ± 5.6
	SB	1	0.600	22.9 ± 1.9	17.8 ± 6.0
Weekly yield (kg)	BTM	1	0.068	1.96 ± 0.76	1.42 ± 0.75
	SB	1	0.062	2.09 ± 0.76	1.62 ± 0.86
Cumulative yield (kg)	BTM	1	**0.001**	6.26 ± 1.35	2.20 ± 0.85
	SB	1	**0.009**	7.98 ± 1.39	5.52 ± 1.72

Table 3.11. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2016 experiments that compare two different planting dates; early planting treatment (3/11) and late planting treatment (6/11) for tomato varieties. Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$.

3.11A. Data subset to tomatoes, with each subset including data over all three varieties and over all harvest dates. 3/11, n = 60; 6/11, n = 59.

	K-W ANOVA		Mean ± standard error	
Yield	**d.f.**	**p value**	**3/11**	**6/11**
Total yield (kg)	1	**0.039**	4.26 ± 0.65	0.22 ± 0.32

3.11B. Data subset to each tomato variety Black Cherry (BC), New Yorker (NY), and Pink Berkeley Tie Dye (PBTD), with each subset including all harvest dates. n = 20; except PBTD: 6/11, n = 19.

		K-W ANOVA		Mean ± standard error	
Yield	**Var**	**d.f.**	**p value**	**3/11**	**6/11**
Total yield (kg)	BC	1	0.681	1.45 ± 0.49	0.14 ± 0.04
	NY	1	**0.001**	6.04 ± 1.11	0.28 ± 0.07
	PBTD	1	**0.026**	5.30 ± 1.36	0.25 ± 0.10
Weekly yield (kg)	BC	1	**<0.001**	0.14 ± 0.03	0.01 ± 0.00
	NY	1	**<0.001**	0.55 ± 0.09	0.03 ± 0.00
	PBTD	1	**<0.001**	0.49 ± 0.08	0.02 ± 0.01
Cumulative yield (kg)	BC	1	**<0.001**	0.50 ± 0.08	0.02 ± 0.01
	NY	1	**<0.001**	1.40 ± 0.19	0.04 ± 0.01
	PBTD	1	**<0.001**	1.80 ± 0.24	0.02 ± 0.01

Table 3.12. Results from Kruskal-Wallis (K-W) non-parametric ANOVAs for subsets of data from Summer 2016 experiments that compare differences in tomato variety (Black Cherry (BC), New Yorker (NY), and Pink Berkeley Tie Dye (PBTD)) within a single planting date (PD). Means and standard errors are shown for the three response variables of total yield (total amount of marketable produce harvested over all harvest dates), weekly yield (amount of marketable produce harvested over each week), and cumulative yield (amount of marketable produce harvested over all weeks prior to and including a particular week). Bold p values indicate significant at $P \leq 0.05$; means with the same letter within a row are not significantly different. n = 20; except PBTD: 6/11, n = 19.

		K-W ANOVA		Mean ± standard error		
Yield	**PD**	**d.f.**	**p value**	**BC**	**NY**	**PBTD**
Total yield (kg)	3/11	2	**0.015**	1.45^{b} ±0.49	6.04^{a} ± 1.11	5.30^{ab} ± 1.36
	6/11	2	**0.050**	0.14^{b} ± 0.04	0.28^{a} ± 0.07	0.25^{b} ± 0.10
Weekly yield (kg)	3/11	2	**0.024**	0.14^{b} ± 0.03	0.55^{a} ± 0.09	0.49^{a} ± 0.08
Cumulative yield (kg)	3/11	2	**0.001**	0.50^{b} ± 0.08	1.40^{a} ± 0.19	1.80^{a} ± 0.24

FIGURES

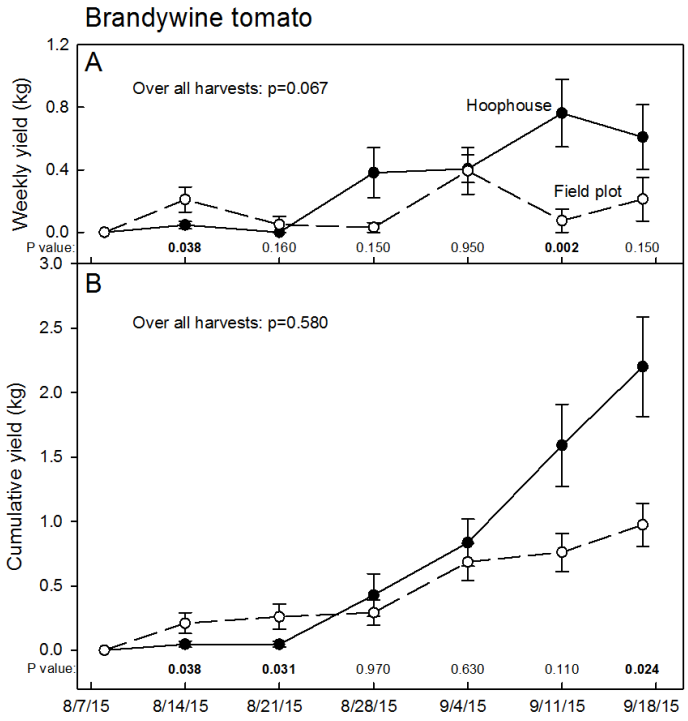

Fig. 3.1. Hoophouse (filled symbols, solid lines) and field plot (open symbols, dashed lines) (A) weekly and (B) cumulative yield for Brandywine tomato plants grown during summer 2015. Bold P value indicates significant ($P \leq 0.05$) difference between hoophouse and field plot yield on a given harvest date. Bars indicate standard errors (n = 16, HH; n = 8, FP).

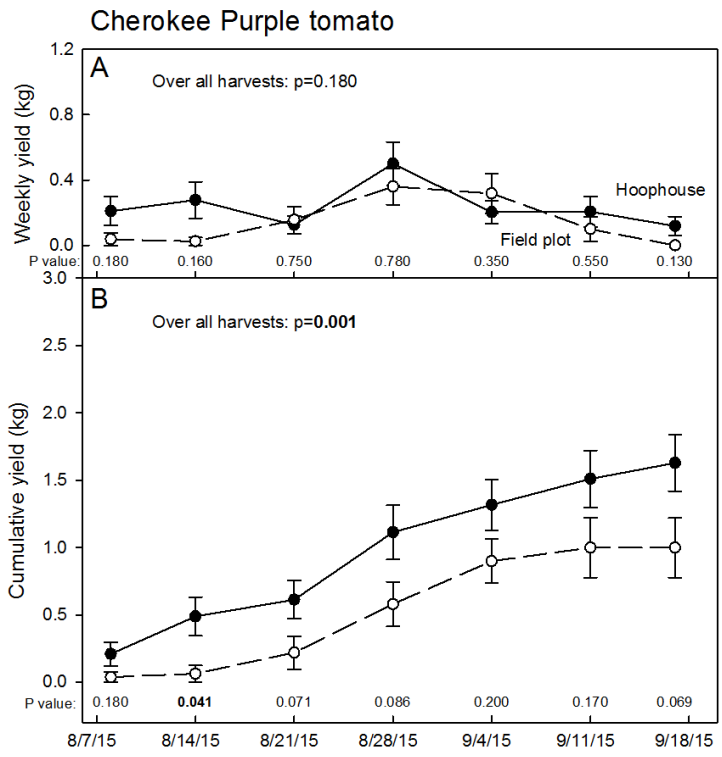

Fig. 3.2. Hoophouse (filled symbols, solid lines) and field plot (open symbols, dashed lines) (A) weekly and (B) cumulative yield for Cherokee Purple tomato plants grown during summer 2015. Bold P value indicates significant ($P \leq 0.05$) difference between hoophouse and field plot yield on a given harvest date. Bars indicate standard errors (n = 16, HH; n = 8, FP).

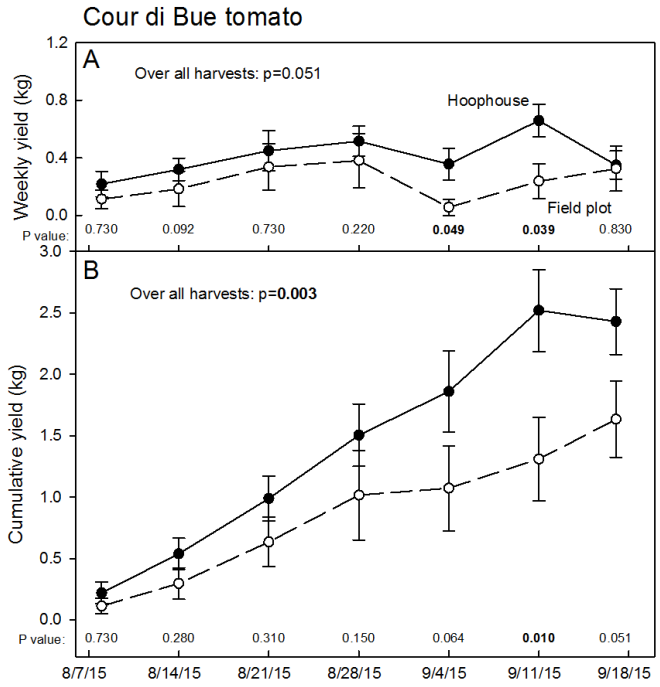

Fig. 3.3. Hoophouse (filled symbols, solid lines) and field plot (open symbols, dashed lines) (A) weekly and (B) cumulative yield for Cour di Bue tomato plants grown during summer 2015. Bold P value indicates significant ($P \leq 0.05$) difference between hoophouse and field plot yield on a given harvest date. Bars indicate standard errors (n = 16, HH; n = 8, FP).

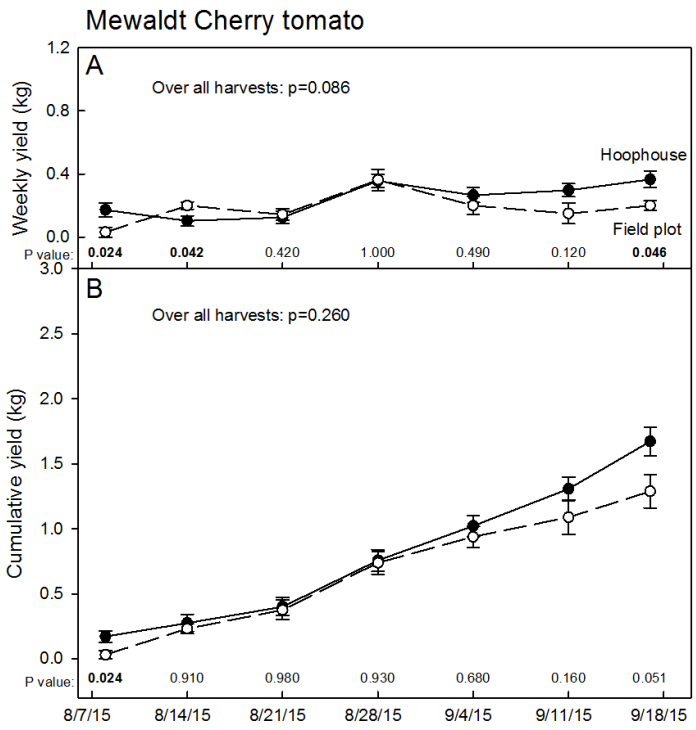

Fig. 3.4. Hoophouse (filled symbols, solid lines) and field plot (open symbols, dashed lines) (A) weekly and (B) cumulative yield for Mewaldt Cherry tomato plants grown during summer 2015. Bold P value indicates significant ($P \leq 0.05$) difference between hoophouse and field plot yield on a given harvest date. Bars indicate standard errors (n = 16, HH; n = 8, FP).

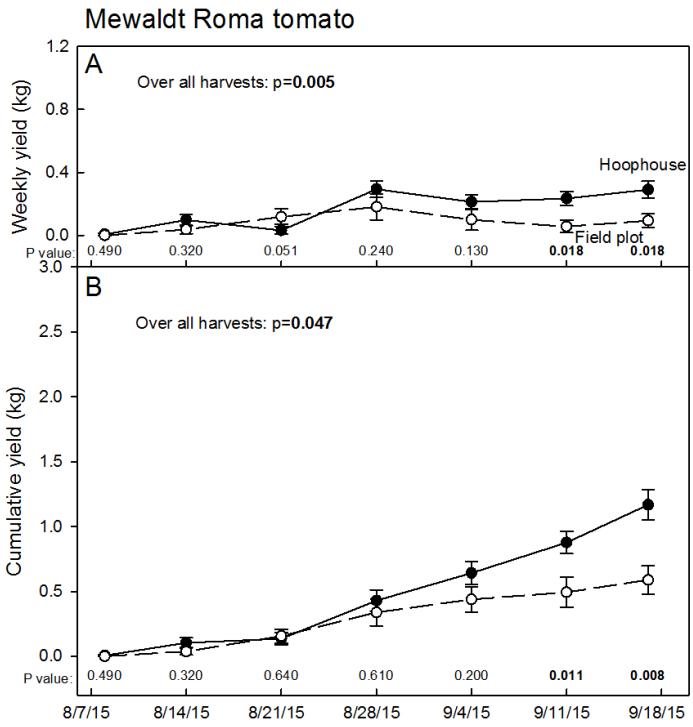

Fig. 3.5. Hoophouse (filled symbols, solid lines) and field plot (open symbols, dashed lines) (A) weekly and (B) cumulative yield for Mewaldt Roma tomato plants grown during summer 2015. Bold P value indicates significant ($P \leq 0.05$) difference between hoophouse and field plot yield on a given harvest date. Bars indicate standard errors (n = 16, HH; n = 8, FP).

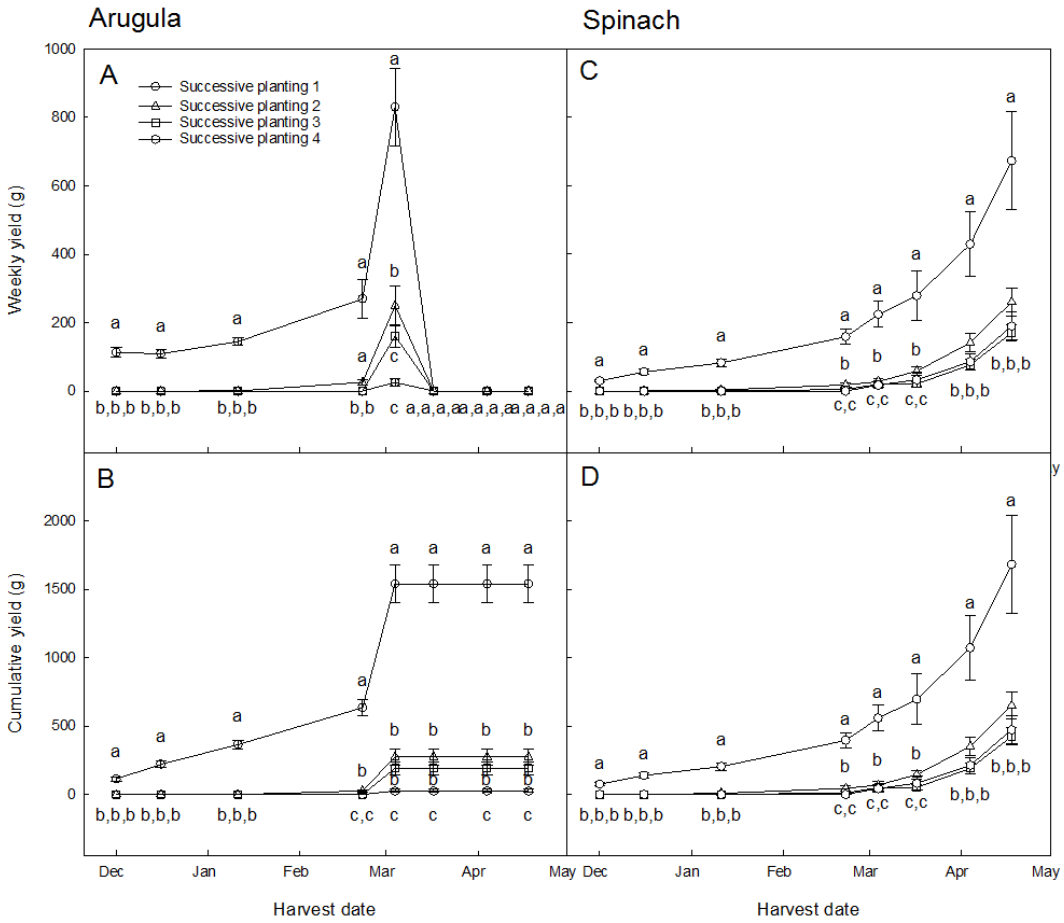

Fig. 3.6. During the winter 2015-2016 experiment, (A) weekly yield of arugula plants, (B) cumulative yield of arugula plants, (C) weekly yield of spinach plants, and (D) cumulative yield of spinach plants of four successive plantings, sown beginning on Oct 2 (circles) and every three weeks until Dec 4 (triangle, square, hexagon), over harvest date. Bars indicate standard error (n = 16). Means with the same letter were not significantly different ($P \leq 0.05$) among successive plantings on a particular harvest date. Letters are in order of successive planting 1, 2, 3, 4 and separated in a similar manner on each harvest date; letters appear from top to bottom, left to right.

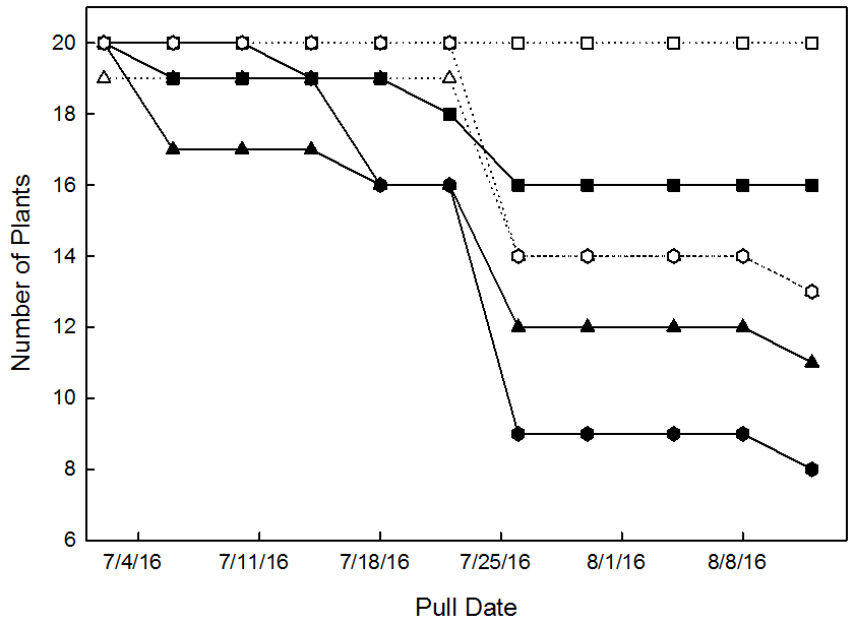

Fig. 3.7. Tomato plant loss in the hoophouses during summer 2016 experiment over the growing season. Filled symbols and solid lines indicate early (3/11) planting treatment and open symbols and dotted lines indicate late (6/11) planting treatment. Number of plants began at n = 20; except late Pink Berkeley Tie Dye (PBTD), n = 19. PBTD (triangles); New Yorker (NY, squares); Black Cherry (BC, circles).

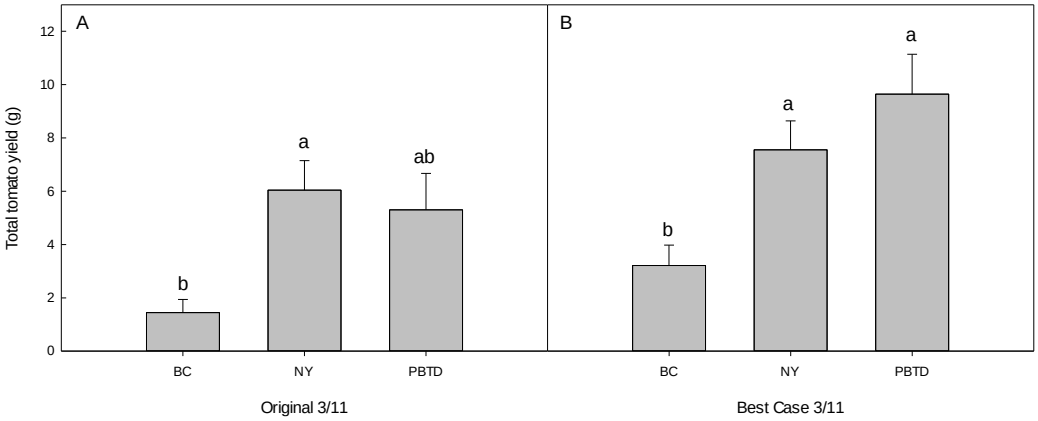

Fig. 3.8. Total yield of Black Cherry (BC), New Yorker (NY), and Pink Berkeley Tie Dye (PBTD) tomato varieties in the early (3/11) planting treatment from (A) the original dataset (BC, NY, n = 20; PBTD, n = 19), and (B) the best case scenario dataset (BC, n = 9; NY, n = 16; PBTD, n = 11). Bars indicate standard errors. Means with the same letter were not significantly different ($P \leq 0.05$).

Chapter 4: Overall Conclusion

Although the effect of wind on plants is complex and variable dependent on planting density and growing environment, higher planting densities were predicted to prevent leaf change from wind treatments. Additionally, higher quality lettuce was expected as a result of wind treatments. However, we saw the opposite effect during all experiments. High planting densities and cooler temperatures did not completely impede leaf response to wind in the hoophouse. Lettuce exposed to natural conditions within the hoophouse was not significantly different than lettuce that was surrounded by a barrier to eliminate leaf movement or any of the wind treatment combinations applied. This lack of response may indicate high planting densities actually buffer plants from wind and the negative leaf effects associated with wind. During the low density experiments, SLA of the lamina portion of the leaf was increased at 6 m s^{-1}, suggesting that wind altered leaf microclimate and leaf water balance that in turn reduced lamina thickness. Unfortunately over all experiment types, lettuce quality was reduced, indicating that the application of wind at the production scale does not appear to be a practical cultivation technique.

Warm and cool season crops benefited from growth in hoophouses during all experiments conducted at the Main Station Field Lab. Applying compost as a mulch treatment benefited watermelon cumulative yield in both hoophouses and field plots. Total yield over both watermelon varieties grown in the hoophouses was significantly greater than field plots in both warm season experiments. However, an early planting date of March 11 for season extension of watermelon plants may not generate substantially greater yield compared to June 11 if soil and air temperatures are not near the optimal growth range for this crop. Tomato plants overall benefited from hoophouse growth compared to field plots. Tomato plants also benefited considerably from early season extension by increasing yield by almost 19 times compared to the late planting treatment. However, the extent each variety benefited from hoophouses and early season extension varied, so consideration of variety is important. Comparing the two warm season

experiments, field plot yield was more variable than hoophouse yield, suggesting that hoophouses can provide a more consistent and reliable year to year production of crops. Additionally, heirloom tomato and watermelon plants benefited from hoophouses by reducing environmental plant stressors and managing rodent problems. Cool season crops typically had zero yield in field plots due to frost heaving of the soil surface resulting in plant death. In the hoophouses, cool season leafy green crops planted no later than early October generated yield throughout the winter months compared to later successive planting dates and also generated a head start on spring harvest for kale and spinach. Because of the benefits of repeat harvest crops, these crops may be a better winter option than single harvest crops for production in hoophouses. Hoophouses are therefore an important growing environment in the high desert of northern Nevada.

Appendix

Fig. A.1. Lettuce grown at production scale density.

Fig. A.2. Lettuce grown in hoophouses at the Desert Farming Initiative, University of Nevada, Reno.

Fig. A.3. Hoophouse Spring 2016 setup.

Fig. A.4. Greenhouse (A) high and (B) low density experiments at the Nevada Agricultural Experiment Station.

A. B.

Fig. A.5. Replicate wind treatment combinations of the greenhouse high density tray experiment at the Nevada Agricultural Experiment Station, University of Nevada, Reno.

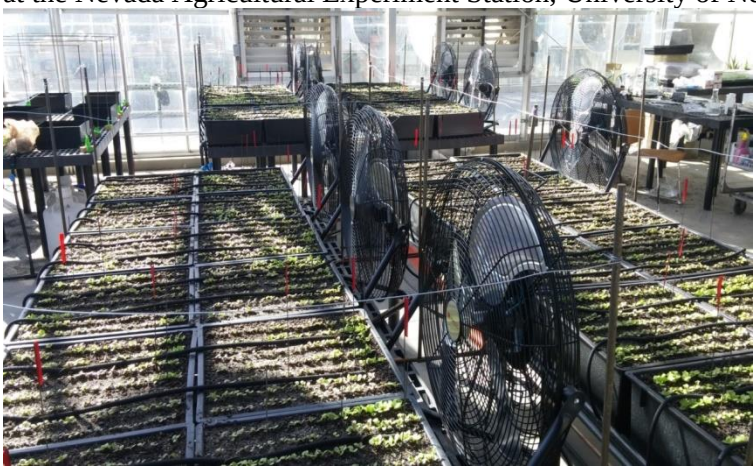

Fig. A.6. Main Station Field Lab, University of Nevada, Reno.

Fig. A.7. Orientation of hoophouses and field plots at the Main Station Field Lab.

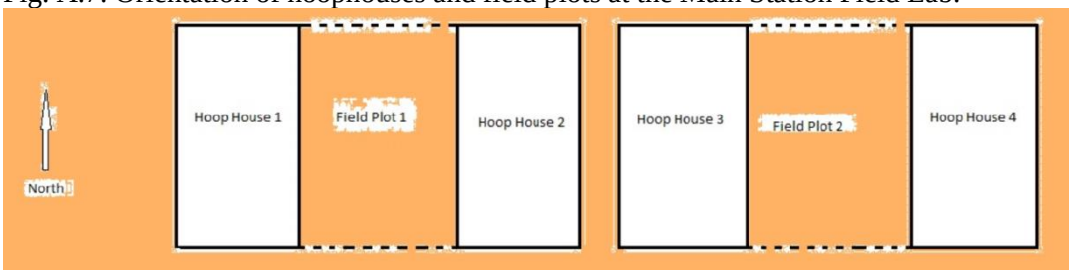

Fig. A.8. Raised beds within (A) hoophouses and (B) field plots.

A. B.

Fig. A.9. Mulch treatments during summer 2015 experiment.

Fig. A.10. Trellised tomato plants using T-post design and vertical string to support all stems.

Fig. A.11. Trellised watermelon plants with fruit support.

Fig. A.12. Successive planting 1during winter 2015-2016 experiment.

Fig. A.13. Early (3/11) versus late (6/11) planting treatment during summer 2016 experiment.

Fig. A.14. Early (3/11) planting treatment watermelons (A) May 4 and (B) June 20.

A. B.

Fig. A.15. Early (3/11) planting treatment tomatoes (A) May 4 and (B) June 20.

A. B.